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MATHEMATICAL MODELING AND ANALYSIS OF THE RELIABILITY OF THE NAVIGATION COMPLEX

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The article examines the navigational complex as a queuing system and defines the correlation between the difficulty of sailing conditions and system capability. A mathematical model for calculating the servicing probability was developed. Recommendations for necessary measures to maintain the appropriate level of system reliability are proposed.The implementation issues of the e-Navigation concept in the International Maritime Organization (IMO) are examined in this paper. In 2014, the IMO adopted the e-Navigation Strategic Implementation Plan (SIP). This plan aims to assess the impact of e-Navigation applications in reducing navigational accidents, such as ship collisions and groundings, as defined by the International Convention for the Safety of Life at Sea (SOLAS). The expected outcome is a substantial decrease in such accidents, projected to be around 65 percent. The responsibility for the safety of navigation and efficient vessel traffic lies with the Member States of IMO, both at the international and national levels. In order to introduce new concepts and innovative systems into vessel traffic, it is essential to thoroughly evaluate their potential effects on both SOLAS ships and non-SOLAS ships. The objective of this paper is to provide a detailed and well-founded assessment of the potential benefits of e-Navigation. To achieve this, we will be exploring and utilizing the International Maritime Organization's (IMO) methodology for measuring these effects. Additionally, we will be examining the application of e-Navigation solutions to non-SOLAS ships, ensuring a comprehensive analysis. In this discourse, the issue encompassing the identification and resolution of faults in information measuring systems is deliberated upon. Considered are the methods used for reconditioning defective systems following information failures. It is recommended to enhance continuous measurements by incorporating specific attributes related to sailing conditions and the technical state of the systems.

Key words: *navigation systems; queuing systems; system stability; technical factor; flow of requests; system failure and recovery; quadratic approximation.*

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Introduction. The safety of maritime transportation depends solely on the secure condition of a ship's deck and machinery. Achieving this necessitates seafarers, analysts, and researchers to possess a robust technical knowledge and expertise. The reports from the Marine Accident Investigation Branch (MAIB) from 1993 to 2012 indicate that 6,692 maritime incidents have been attributed solely to technical factors, while 69% of incidents involved a combination of other factors. The technical factors encompass a range of aspects such as main/auxiliary/deck machinery, bridge procedures, maneuverability, collision/contact, electrical systems, fire and explosion precautions, flooding and foundering risks, general management and procedures, shipboard activities, grounding hazards, hazardous incidents, navigation and communication equipment, operational design considerations, pollution concerns, stability measures, structural integrity, safety equipment, and emergency response protocols, among others. Throughout human existence, one of the most widely recognized approaches has been to extract valuable insights from past undesirable events, which in turn helps individuals overcome potential recurrences [1].

The aim of the Strategic Implementation Plan (SIP) is to assess the impact of e-Navigation in order to minimize navigational incidents such as collisions and groundings, achieving a significant 65% reduction specifically for SOLAS vessels. The situation of maritime safety varies from country to country. In real maritime practices, SOLAS ships often come into contact with non-SOLAS ships. The practices for implementing e-Navigation may vary across countries due to differences in their priorities, levels of readiness, and expected outcomes in applying it to their water areas. By establishing an effective and efficient National SIP, this aids member states in maximizing the benefits of implementing e-Navigation for their water areas.

National authorities are responsible for investigating and monitoring their respective situations concerning their national waters and shipping fleets. The authors of this paper present a novel approach for effectively evaluating the implementation of e-Navigation applications [2]. The focus of the method is to quantify the impact of e-Navigation solutions in terms of reducing accidents that can potentially be avoided with the use of e-Navigation applications. The method will be presented and examined through the Korean SMART-Navigation project, which offers e-navigation services for both non-SOLAS and SOLAS ships. This project serves as a model case for a comprehensive assessment of e-Navigation implementation, considering the unique circumstances and conditions of coastal states. Within the context of this project, specialized solutions are introduced in the form of e-Navigation toolkit applications. The presentation will unveil the results of extensive research conducted by the World Maritime University in collaboration with various partners. This research aims to identify the training requirements and user preferences necessary for the successful implementation of cutting-edge e-Navigation solutions in practical settings.

The integrated marine system encompasses several components, which include inertial navigation systems (INS), a receiver for satellite navigation system (SNS), a log, and a computer dedicated to processing and monitoring information. Anomalous gyro drifts and accelerometer biases are identified as the primary information failures observed in the INS sensors.

Analysis of recent research and publications. The literature extensively addresses the problem of detecting faults (FD) in information failures and the development of systems that can withstand these faults. The mathematical formulation of the problem related to information measuring systems (IMS) in the context of Fault Detection (FD) relies on the principles of statistical decisions. It involves conducting hypothesis tests to determine whether faults are present or absent within the system. Two classes can be distinguished among the methods employed to solve this problem - snapshot and sequential methods. The former relies on individual measurements for decision-making, whereas the latter requires a series of consecutive measurements. In this paper, we explore a method to solve an FD problem by utilizing a measurement sequence. To solve this type of problem, we need to introduce a dynamic model for the IMS errors in both the nominal state and faulty states, along with state transition models. As mentioned earlier, solving a combined problem of hypothesis testing and failure estimation is imperative. Using the posteriori probabilities of hypotheses, the system's fault tolerance is improved, as indicated by the weighted estimate of parameters [3].

The autonomous navigation function is supported by the system components identified, which ensure safe decision-making and execution. These components encompass route planning, voyage management, collision avoidance, and situation awareness. The absence of crew onboard to take control of navigation increases the risk of severe navigational accidents, including collisions with other ships, surface and underwater obstacles, and grounding. This risk is primarily caused by failures in the autonomous navigation system (ANS) software, hardware, and power supply. In order to guarantee the safety of the system under investigation, it is advisable to incorporate backup measures for the essential ANS components, such as software, hardware, power supply source, Echo Sounding System, ECDIS, and microphone [4–7].

The redundancy of safety-critical systems or sensors may indeed ensure sufficient safety levels for complex systems like the ANS. However, this method is not the most cost-effective option. In order to enhance performance and efficiency, it is advisable to incorporate upgraded versions of vital components and sensors that offer longer mean time between failure (MTBF). Additionally, employing intelligent software like health monitoring for sensors can help in timely detection of issues and scheduling necessary maintenance tasks. In conclusion, the safety levels of the conceptual software mentioned in the investigated system must be defined through validation and verification [8, 9].

Purpose and objectives of the research. In today's era, the prevalence of surplus equipment is more frequent than its scarcity, and this is frequently reasonable. The navigation equipment malfunction can cause significant financial loss for both the shipowner and the shipper, which is not desirable considering the high value of the cargo and the ship. The cost of the equipment itself is relatively small compared to the overall expenses involved [10].

A well-established method for evaluating the efficiency of technical systems is through the use of queueing system theory. This theory enables us to calculate the probabilities of different conditions within queuing systems (QS) and ascertain the relationships between specific parameters of QS and their effectiveness measures.

Given that all channels in the system are basic, the processes the QS is currently experiencing can be described as a Markov random process. This process consists of discrete states and occurs over continuous time. In the event that the process satisfies the ergodicity conditions, a final stationary mode is attained. In this mode, the probabilities of states and other process parameters remain unaffected by time. Researchers often find themselves focusing on these well-established and long-standing traits for their study [11].

The ship officer's job will be analyzed as a single-channel QS that has a tendency to fail. To begin, it is essential to acknowledge that the officer has the responsibility of managing various streams of requests. While on duty, he must not only pay attention to the surrounding environment but also record approximately 10 parameters including course, speed, power, and various others. Neglecting failure states in others may be a consequence of focusing all attention on one. Decisions will have to be made promptly in these circumstances, inducing stressful scenarios that might lead to errors.

Main body. The irregular flow of applications and their varying service time cause the QS to be loaded inconsistently. There are instances where unserved orders accumulate at the input, resulting in an overloaded QS. Conversely, there are situations where the QS entrance has available channels but no applications, leading to an underloaded QS and idle state of its channels. The entrance of the QS is where orders pile up. These orders have two possible outcomes: they either join the queue or, if it is not possible for them to wait any longer in the queue, they will leave the QS without being served [12].

Consequently, there is a possibility for the working channel (ship officer) to encounter glitches and cease functioning to some extent. This can be triggered by various factors such as illness, loss of consciousness, or extreme stress leading to a mental freeze-up. The capability to swiftly evaluate the circumstances and make prompt judgments is inadvertently diminished.

Once a channel malfunctions, the recovery process commences promptly after the occurrence. This may manifest as regaining consciousness, consuming appropriate medication to remedy an illness, or successfully recovering from a lock-up event.

The birth-death graph represents the system's states and is depicted as follows:

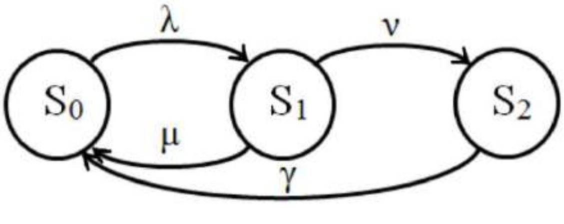

Figure 1 – QS state graph

where S_0 – channel is free;
S_1 – channel is busy (working), good;
S_2 – channel failed, restored.

Allow the most basic flow of requests to reach its input with an intensity denoted byλ. Service time – exponential with parameter $\mu = \frac{1}{\bar{t}_{обсл}}$, where $\bar{t}_{обсл}$ – average request service time. This implies that the service flow is the most uncomplicated, namely, a stationary Poisson process can be described by an intensity parameter, denoted asμ. There is a possibility that a functional channel may fail – decline. Let us make the assumption that the intensity ν is at its simplest form in relation to the flow of failures. Immediately after a channel failure, the process of channel recovery commences. The repair time for the channel follows an exponential distribution characterized by a parameter known as intensity$\gamma = \frac{1}{t_p}$, where t_p – average recovery time (repair). In [11], the problem was expressed in a similar manner, focusing on the navigator as a service channel. In the present study, the complexity of the problem arises from considering the potential occurrence of a channel failure and its impact on an idle state, denoted by an intensity ν'. It is reasonable to assume that $\nu' < \nu$ [13].

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

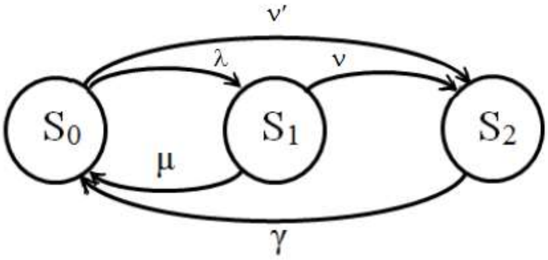

Figure 2 – QS state graph with failure possibility during idle

Theory of system reliability has various approaches towards considering the reliability of complex equipment, such as navigational systems or ship machinery. Failure mode effect and criticality analysis (FMECA) is extensively used in maintenance and risk analysis to ensure a comprehensive comprehension of potential failures, their causes, and possible corrective measures [14]. This approach outlines the ways in which things can go awry, identifies the reasons behind these failures, and offers insights into rectification or mitigation strategies. The Criticality Analysis (CA) is used to identify events, occurrences, or components that require greater attention to prevent more severe or catastrophic situations [15]. FMECA offers a systematic methodology to comprehensively understand the causes and effects of failures on a specific equipment or system, following a bottom-up perspective. Measuring criticality through FMECA aids in identifying the most crucial component failure, thus supporting maintenance actions and planning by uncovering explicit information. Subjective operator inputs were collected using FMECA, which can be described in two ways. One aspect to focus on is the assessment of operator sentiments and priorities, particularly regarding failures and maintenance challenges. This includes analyzing factors like expertise and identifying reasons behind prolonged downtimes. Additionally, this technology served the purpose of identifying crucial faults in maintenance and machinery components. In terms of writing, the second aspect involved the validation of crucial components acquired through qualitative analysis using DFTA. In order to achieve these two goals through FMECA analysis, a questionnaire was created and disseminated using the Qualtrics survey software.

The main objective of the survey was to identify the components that pose the biggest challenge to carrying out maintenance work onboard, by utilizing the risk priority number (RPN) [16]. The RPN employs three categorical variables, namely identification, severity, and likelihood. These variables are typically measured on a linear scale that reflects their increasing importance. The scale used for the analysis is presented in Table 1, which shows the linear scale and the Likert scale, including color codes representing the corresponding scale values [17, 18].

The Risk Priority Number (RPN) is determined by considering the severity of the failure's impact, the probability of its occurrence, and how easily it can be detected for each failure mode. In accordance with the following formula, RPN is obtained by multiplying these three numbers:

$$RPN = S \times P \times D \quad (1)$$

where S – the severity of the effect of failure;
P – the probability of failure;
D – the ease of detection.

Although RPN may not have a significant impact on deciding the course of action against failure modes, it can assist in identifying the threshold values that determine the areas requiring the most attention. To put it differently, the analysis and corrective action should prioritize failure modes with a high RPN number [19].

Table 1 – Definition of Criteria

Linear scale (1–10)	***Severity Level***	***Criticality Level***	***Likelihood Level***	***Failure Rate***
1	**Minor:** Failure or event that has little or no significant impact to system capability and availability.	**Minor:** A component failure or event that has no immediate impact on platform or personnel safety.	**Remote:** Failure is unlikely.	10^{-5}–10^{-6}
2–3	**Low:** Failure or event that could cause slight deterioration of system capability but will not affect it availability. System may require minor repair action.	**Low:** Failure or event that could cause slight delay/deterioration system capability but will not affect its availability.	**Low:** Isolated failure associated with component or equipment.	10^{-4}–10^{-5}
4–6	**Marginal (Moderate):** Failure could result to deterioration in system capability which may require unscheduled repair or may cause minor health hazard or injury to the user.	**Marginal (Moderate):** A failure that could result to deterioration in system capability and availability which may require unscheduled repair that can be conducted by ship staff.	**Moderate:** Occasional failure but not in major proportions.	10^{-3}–10^{-4}
7–8	**Critical (High):** Failure causes loss of system capability and availability or may cause a serious health hazard or serious injury to the user.	**Critical (High):** Failure that results to loss of system capability and can influence the efficient operation of other systems.	**High:** Generally associated with components or system which often fail.	10^{-2}–10^{-3}
9–10	**Major (Very High):** A potential failure could cause complete system loss and/or death of user(s). A failure event which may lead to extended downtime due to spare parts or OEM assistance.	**Major (Very High):** A potential failure could cause complete system loss that will require FSG or OEM assistance.	**Very High:** A component or equipment with very high failure rate,	10^{-1}–10^{-2}

Results of research. We shall proceed to determine the ultimate probabilities of the system's states as well as the attributes of its effectiveness: A, denoting absolute throughput, and Q, representing the relative throughput (the probability of successfully handling an incoming request).

The final probabilities of states in the algebraic system of equations, derived from the Kolmogorov differential equations by setting the left-hand side (state probability derivatives with respect to time) to zero, can be expressed as follows:

$$\begin{aligned}(\lambda+\nu')p_0 &= \mu p_1+\gamma p_2\\ (\mu+\nu)p_1 &= \lambda p_0\\ \gamma p_2 &= \nu p_1+\nu' p_0\end{aligned} \tag{2}$$

Additionally, the condition of normalization to unity can be incorporated into this system:

$$p_0+p_1+p_2=1 \tag{3}$$

The task is to discover the intended ultimate probabilities:

$$p_0 = \left[1 + \frac{\lambda}{\mu + \nu} + \frac{\lambda\nu + \mu\nu' + \nu\nu'}{\gamma(\mu + \nu)}\right]^{-1} \tag{4}$$

$$p_1 = \frac{\lambda}{\mu + \nu} p_0 \tag{5}$$

$$p_2 = \frac{\lambda\nu + \mu\nu' + \nu\nu'}{\gamma(\mu + \nu)} p_0 \tag{6}$$

In order to determine the relative throughput, we apply the principles stated in [10] and obtain:

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

Absolute throughput:

$$A = \lambda Q = p_0 \frac{\lambda\mu}{\mu + \nu} \tag{8}$$

After simplifying the expression for Q, it can be written in a form suitable for numerical calculation as follows:

$$Q = \frac{\mu\gamma}{(\mu + \nu)(\gamma + \nu') + \lambda(\gamma + \nu)} \tag{9}$$

The servicing probability of the incoming request Q is determined by five parameters. These parameters are the intensities of the corresponding flows: λ, μ, γ, ν и ν'.

We will now calculate the value of Q for different combinations of the parameters mentioned above.

The calculations for probabilities of incoming request fulfillment under various sailing conditions and intensities of incoming request streams, failure streams, and recovery streams can be seen in Figures 3–8.

Figures 3–4 illustrate the correlations observed during favorable sailing conditions, specifically in open seas and oceans. The intensity of the request stream increases from 2 to 6 per hour, resulting in a decrease in the probability of fulfilling the requests. To achieve a high probability Q (nearing 1), one can enhance the capacity of both the servicing channel and recovery channel.

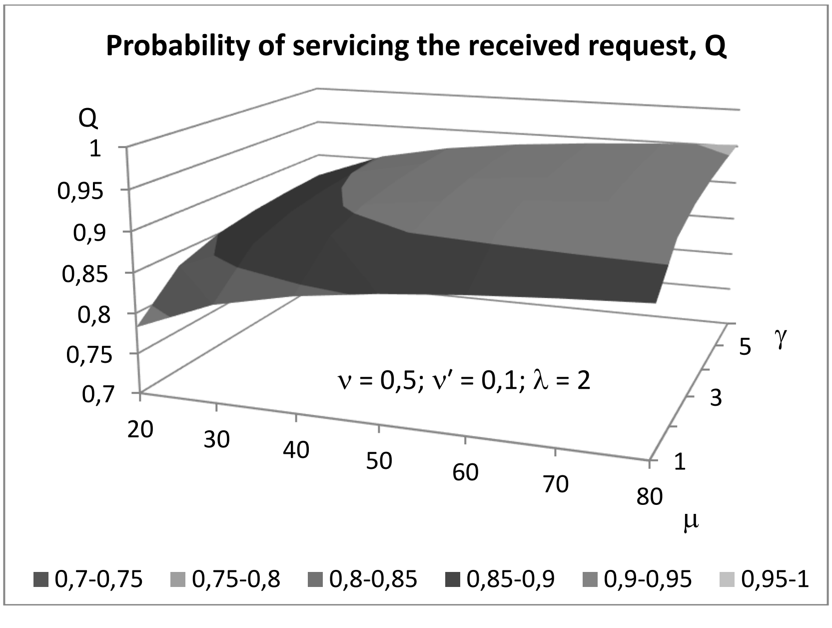

Figure 3 – The correlation between Q and λ, μ, γ, ν, ν'. The intensities of the corresponding streams are as follows: ν = 0,5 per hour; ν' = 0,1 per hour; λ= 2; μ from 20 to 80 per hour; γ from 1 to 6 per hour

$$Q_{\text{т}} = 0,6824 \pm 0,0079 + (0,0474 \pm 0,0029)\gamma + (-0,0047 \pm 0,0004)\gamma^2 + (0,0041 \pm 0,0003)\mu + (-2,7579 \times 10^{-5} \pm 0,2881 \times 10^{-5})\mu^2 \quad (10)$$

$$R^2 = 0,9765;\ \sigma = 0,0065.$$

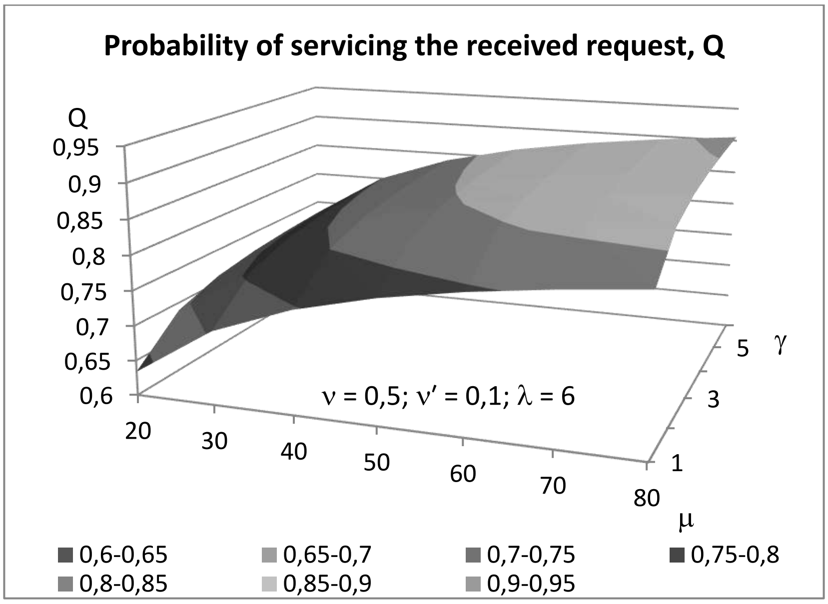

Figure 4 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding streams are as follows: ν = 0,5 per hour; ν′ = 0,1 per hour; λ= 6; μ from 20 to 80 per hour; γ from 1 to 6 per hour

$$Q_{\text{т}} = 0,4641 \pm 0,0104 + (0,0525 \pm 0,0038)\gamma + (-0,0052 \pm 0,0005)\gamma^2 + (0,008 \pm 0,0004)\mu + (-5,2609 \times 10^{-5} \pm 0,3793 \times 10^{-5})\mu^2 \quad (11)$$

$$R^2 = 0,9855;\ \sigma = 0,0085.$$

The correlations for sailing in coastal zones are shown in Figures 5–6. In this scenario, the failure stream's intensity increases to 1 while the request stream's intensity ranges from 10 to 20. Consequently, the chances of fulfilling requests decrease when compared to the previously mentioned data.

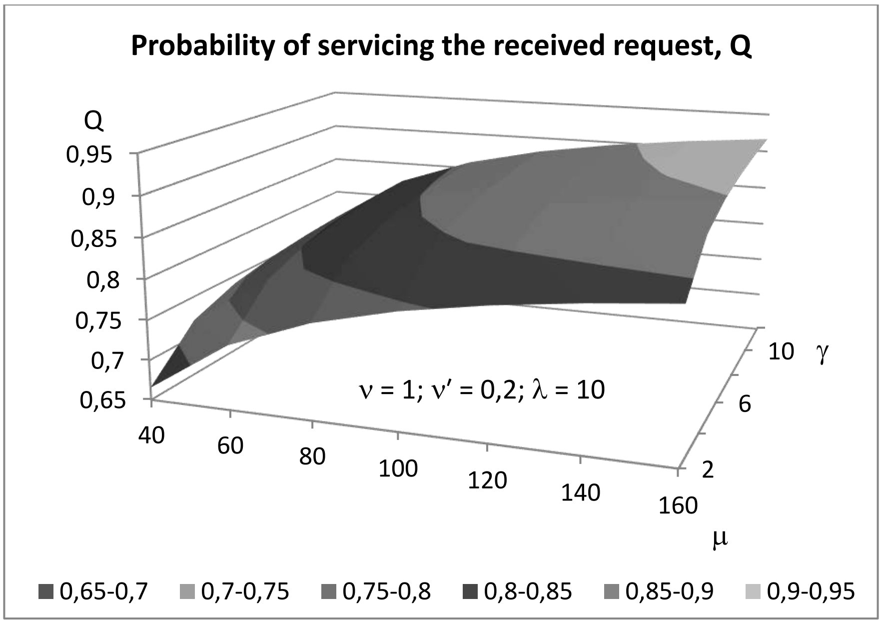

Figure 5 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding streams are as follows: ν = 1 per hour; ν′ = 0,2 per hour; λ= 10; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_{\text{т}} = 0{,}5098 \pm 0{,}01 + (0{,}0258 \pm 0{,}0018)\gamma + (-0{,}0013 \pm 0{,}0001)\gamma^2 + (0{,}0036 \pm 0{,}0002)\mu + (-1{,}2002 \times 10^{-5} \pm 0{,}0912 \times 10^{-5})\mu^2 \quad (12)$$

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

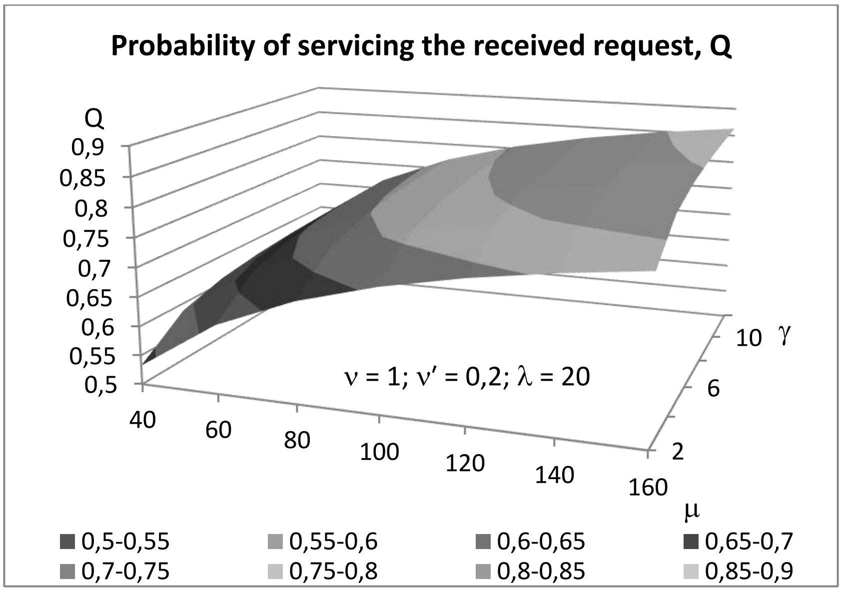

Figure 6 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding streams are as follows: ν = 1 per hour; ν′ = 0,2 per hour; λ= 20; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_{\text{т}} = 0{,}3222 \pm 0{,}011 + (0{,}0275 \pm 0{,}002)\gamma + (-0{,}0014 \pm 0{,}0001)\gamma^2 + (0{,}0051 \pm 0{,}0002)\mu + (-1{,}6011 \times 10^{-5} \pm 0{,}101 \times 10^{-5})\mu^2 \quad (13)$$

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

In challenging navigation conditions such as rivers, ports, dense traffic, and poor visibility, Figure 7–8 illustrates the correlations observed for sailing. The failure stream's intensity is augmented to 5, while the request stream ranges from 20 to 40, leading to a further reduction in the likelihood of a request being fulfilled, as compared to the previous data.

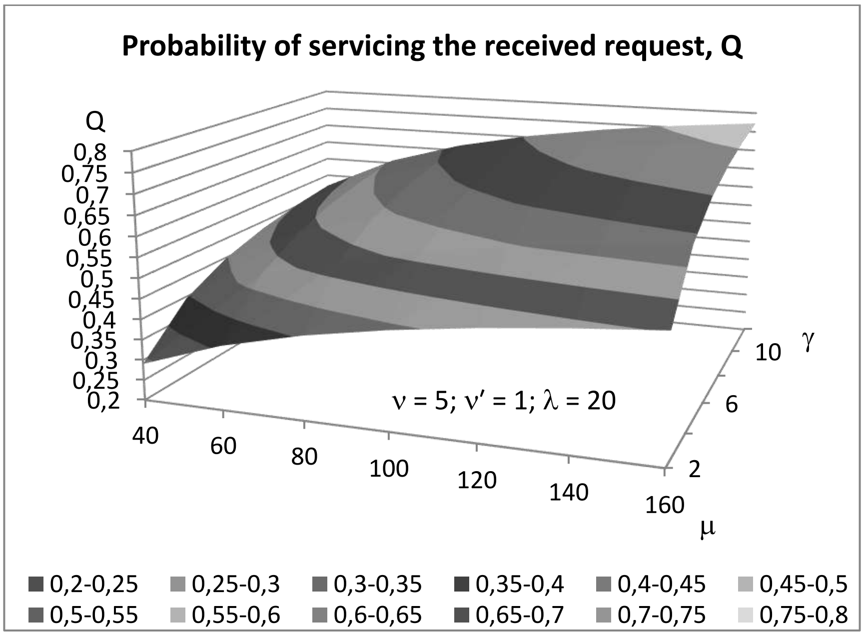

Figure 7 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding streams are as follows: ν = 5 per hour; ν′ = 1 per hour; λ= 20; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_{\text{т}} = -0{,}0095 \pm 0{,}0163 + (0{,}0667 \pm 0{,}003)\gamma + (-0{,}0031 \pm 0{,}0002)\gamma^2 + (0{,}0049 \pm 0{,}0003)\mu + (-1{,}5023 \times 10^{-5} \pm 0{,}1487 \times 10^{-5})\mu^2 \qquad (14)$$

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

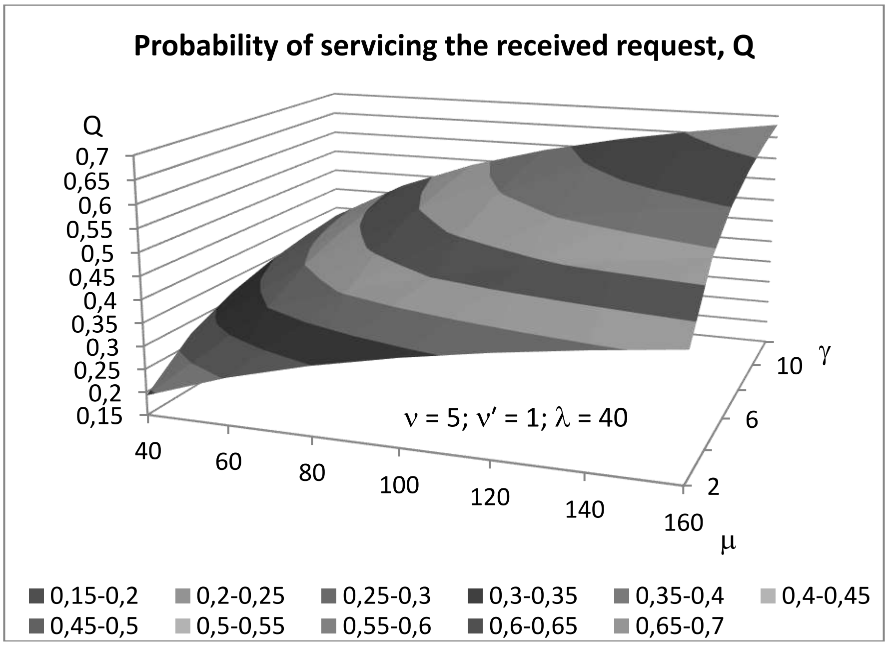

Figure 8 – The correlation between Q and λ, μ, γ, ν, ν′. The intensities of the corresponding streams are as follows: ν = 5 per hour; ν′ = 1 per hour; λ= 40; μ from 40 to 160 per hour; γ from 2 to 12 per hour

$$Q_{\text{т}} = -0{,}1196 \pm 0{,}0171 + (0{,}0604 \pm 0{,}0031)\gamma + (-0{,}0027 \pm 0{,}0002)\gamma^2 + (0{,}005 \pm 0{,}0003)\mu + (-1{,}3831 \times 10^{-5} \pm 0{,}1561 \times 10^{-5})\mu^2 \qquad (15)$$

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

The equations below each graph are derived by applying the square two-factor approximation method. A high level of determination coefficients (R^2=0,98-0,99) indicates that the received statistical square models are highly adequate. The square regressions exhibit remarkably low standard deviations (σ=0,006-0,014), indicating their exceptional accuracy. Consequently, these models can be confidently employed to obtain highly dependable probability assessments [20].

The data are also consistent with the following recommendations for the operation of bridges in various difficult navigation conditions [21].

Table 2 – 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

In order to comply with this condition, it is necessary to have both an Officer of Watch and a Lookout present on the bridge.

The Officer of Watch carries out regular watchkeeping responsibilities, and occasionally assumes the role of the only lookout during daytime. In circumstances that call for manual steering, it is important to note that the helmsman cannot fulfill the role of the lookout. Therefore, it is necessary to assign an extra crew member as a dedicated lookout. The engine room has the capability to operate in both manned and unmanned modes.

Bridge Watch Condition – II

In order to meet this requirement, it is necessary for the following individuals to be present on the bridge: the Master or Chief Officer, the Officer of Watch, the Lookout, and the Helmsman.

The safe navigation and overall watch organization of the crew is supervised by the Master or Chief Officer. Assisting the Master or Chief Officer, the Officer of Watch relays pertinent information, navigates the ship, and monitors the implementation of orders. In situations deemed necessary by the officers or when faced with challenging conditions such as high traffic, limited visibility, port maneuvers, or boarding a pilot, the Helmsman takes control of the vessel's steering manually.

It is essential for the engine room to have a staff available at all times, but it is ultimately up to the Master to decide whether to assign personnel to it or not.

Bridge Watch Condition – III

In order to meet this condition, it is necessary to have the following personnel present on the bridge: the Master, Officer of Watch, Additional Officer, Lookout, and Helmsman.

In case of condition III, the Officer of Watch is relieved of collision monitoring responsibilities, and an Additional Officer assumes this duty by utilizing AIS/ARPA systems. They provide the Officer of Watch with relevant navigational information and data concerning nearby vessels. It is essential to have personnel present and ready in the engine room.

Of interest is the Korean experience in implementing e-navigation systems.The Korean implementation of the IMO e-navigation concept, known as SMART-navigation, is applied to Korean waters and on Korean-affiliated ships. In addition to the IMO e-navigation scope, SMART-navigation extends its services to non-SOLAS ships such as fishing vessels and non-fishing vessels operating in domestic coastal areas. This assumption arises from various reasons, primarily because non-SOLAS ships are more susceptible to accidents compared to SOLAS ships. This susceptibility can be attributed to inadequate navigational equipment, increased workload on board, and limited safety information from shore based stations.

The aim of SMART-Navigation is to offer non-SOLAS ships with extra specialized services, alongside the services provided by IMO e-navigation. The primary objective of the services is to anticipate and prevent possible causes of accidents. This is achieved through proactive support and management of areas that are deemed susceptible to accidents. These determinations are made by analyzing real-time statistics and local situation data, both of which are obtained from shore-based stations. These services encompass:

- Supporting decision-making to prevent accidents is crucial.
- Analyzing maritime safety factors utilizing Big Data.
- Ships, which are at risk of accidents, can receive safety information that is provided to them.
- Providing a streaming service of electronic nautical charts (ENCs).
- Remote support and management of safety training crews is essential for efficient operations.
- The ability to effectively identify and react to all maritime sectors in every region of the Korean waters is imperative.
- Giving information about the activities of illegal unreported unregulated fishing.
- Sharing details on the oil spill.
- Supporting measures to prevent ships from illegally discharging wastes and pollutants.

– Providing assistance for the various endeavors concerning maritime security.

To accomplish these goals, the objective of SMART-navigation is to establish the LTE-Maritime communication network as a foundation for non-SOLAS ships to enable the deployment of essential e-navigation services. Furthermore, the communication networks that are necessary for e-navigation services will be equipped with a data structure reliant on the Common Maritime Data Structure (CMDS). This data structure will incorporate the VHF Date Exchange (VDE), as well as digital HF/MF and satellite-based communication [22].

In order to assess the impact of SMART-navigation in reducing accidents [2], the authors conducted a comprehensive analysis of accident data in Korean waters for all ships and Korean-flagged ships globally from 2009 to 2013. The data presented in this work was obtained from the Korea Maritime Safety Tribunal (KMST). According to the analysis, a total of 4,871 accident vessels were examined. From this, the authors identified 3,366 accident vessels that specifically addressed the detailed direct causes that can be prevented through the Risk Control Options (RCOs) offered by e-navigation.

Table 3 – The ranking of RCOs based on the potential loss of lives (taken from: Annex 1 of NAV 59/6 (p. 37))

Accident Type				*Human Errors*	*Technical Failure*	*External Factor*	*Total*	
							Actual	*Effect*
Non-Fishing Vessels	Navigational Accident	SOLAS	Actual %	465 (13,8%)	–	14 (0,4%)	828 (24,6%)	14,8%
			Risk Reduction Rate	65,1%	–	65%		
			Effect	8,9%	–	0,3%		
		Non-SOLAS	Actual %	338 (10,0%)	–	11 (0,3%)		
			Risk Reduction Rate	55,1%	–	55,0%		
			Effect	5,5%	–	0,1%		
Non-Fishing Vessels	Non-Navigational	SOLAS	Actual %	163 (4,8%)	37 (1,1%)	4 (0,1%)	353 (10,5%)	6,2%
			Risk Reduction Rate	65,3%	64,9%	65%		
			Effect	3,1%	0,7%	–		
		Non-SOLAS	Actual %	119 (3,5%)	27 (0,8%)	3 (0,1%)		
			Risk Reduction Rate	55,2%	54,9%	55%		
			Effect	1,9%	0,4%	0,1%		
	Sum		Actual %	1,085 (32,2%)	64 (1,9%)	32 (0,95%)	1,181 (35,1%)	21,0%
			Effect	19,4%	1,1%	0,5%		
Fishing Vessels	Navigational Accident		Actual %	1,155 (34,3%)	2 (0,1%)	16 (0,5%)	1,173(34,8%)	19,1%
			Risk Reduction Rate	54,9%	55%	54,9%		
			Effect	18,8%	–	0,3%		

Source: KMST investigation statistics and data base (2014).

Table 3 exhibits the impact of SMART-navigation in mitigating accidents. This evaluation was conducted by employing the suggested formula derived from the analysis of accident data. The reduction is anticipated to exceed 56,6% of the total accidents involving 3,366 vessels, comprising 13% of SOLAS ships and 43,6% of non-SOLAS ships, specifically fishing vessels. It is anticipated that there will be a reduction of over 33.9% in navigational accidents. This includes a decrease of 14,8% for non-fishing vessels and 19,1% for fishing vessels. It is anticipated that there will be a decrease of up to 22,7% in accidents, even those that do not involve navigation. This reduction includes a 6,2% decrease for non-fishing vessels and a 16,5% decrease for fishing vessels. The expected reduction in accidents caused by human error is 50,2%. Meanwhile, accidents caused by technical failures are anticipated to be reduced by 5,4%, and accidents caused by external factors by 1%.

Conclusions. By analyzing the simulation results, one can ascertain the impact of the initial parameters on the likelihood of fulfilling an incoming request. Consequently, it becomes feasible to anticipate the stability of the components within the navigation system. The obtained results provide the opportunity to develop suitable recommendations for enhancing the functional stability of the navigation complex. The simulation results demonstrate that as the failure rate intensifies and the request rate increases, the fulfillment probability of incoming requests drastically declines. Consequently, the performance of the navigation complex is affected.

Due to a significant decrease in the chances of failure-free operation of the equipment, it is crucial to plan for the swift replacement of failed modules and blocks in the navigation system. This approach will greatly amplify the pace of restoration. Moreover, in critical situations, it is imperative to establish a "hot standby" to guarantee uninterrupted functioning of the navigation complex.

Alternatively, there is a risk of disconnecting internal components within the system. The gyrocompass, for instance, lacks data on the vessel's speed, causing a deviation in its indicators. If an operator lacks comprehensive understanding of the system's structure and its elements, they will be unaware of this fact. Consequently, it may result in errors while controlling the vessel.

In this manner, by developing the navigation system stability model, it becomes possible to simulate different emergency situations. The simulation revealed the correlation between the system's performance and its parameters: λ, μ, γ, ν, ν'. Contrarily, the system boasts an extensive array of internal connections. Incorrect operation of the system can occur if any one of them is violated.

The research findings highlight the importance of determining the adequate level of duplication for navigation devices to ensure system reliability. If the Q value drops below 0.7, it poses a critical situation onboard the ship. The probability of meeting the request varies based on the sailing's navigational conditions, illustrated in Figures 3–8. Consequently, it becomes necessary to implement measures that guarantee the stability of the navigation system during challenging circumstances.

The study findings have the potential to enhance comprehension regarding the associated dangers and their corresponding levels of risk. Despite the growing interest in this area, as evidenced by the rising number of publications, it is crucial to recognize the scarcity of literature and emphasize the necessity for further research. A recommendation is to adopt a comprehensive hazard analysis, categorizing hazards with greater detail. This approach allows for deeper evaluation of the contributing factors, resulting in more specific and efficient risk management strategies.

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Плотніков В. І., Дудченко С. В., Абрамов Г. С., Макарчук Д. В. МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ТА АНАЛІЗ НАДІЙНОСТІ НАВІГАЦІЙНОГО КОМПЛЕКСУ

У статті досліджено навігаційний комплекс як систему масового обслуговування та визначено співвідношення між складністю умов плавання та можливостями системи. Проведено математичне моделювання та аналіз надійності навігаційного комплексу судна з точки зору теорії масового обслуговування. Представлена робота є однією з піонерських по застосуванню теорії масового обслуговування для аналізу проблем безпечного судноводіння, що забезпечує її актуальність і наукову новизну. Розроблена математична модель доведена до чисельних експериментів і проведена візуалізація отриманих результатів та їх математична обробка шляхом побудови квадратичних апроксимаційних рівнянь, що зв'язують вірогідність робочого стану систем з відповідними інтенсивностями потоків відмов і обслуговування. Математичне моделювання проведено для різних умов складності судноводіння (від відкритого моря, до каботажного плавання і припортових маневрувань). Це забезпечує і високу практичну значимість наведених результатів моделювання при розробці відповідних регламентів судноводіння і при виконанні оцінок потенційних переваг електронної навігації.

Ключові слова: *системи навігації; системи масового обслуговування; стійкість системи; технічний фактор; потік запитів; потік відмов; потік обслуговування; відмова та відновлення системи; квадратична апроксимація.*

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