

## **IMPACT OF THE HUMAN OPERATOR FACTOR IN RATIONAL MANAGEMENT OF MARINE TECHNICAL SYSTEMS AND COMPLEXES**

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**Introduction.** In the modern world of technology and innovative technical systems, the interaction between the human operator and automated control systems plays a crucial role in the safety and efficiency of navigation. Despite significant achievements in the field of automation, the human factor remains one of the most unpredictable elements in the ship's technical system management chain [1–3]. This study is dedicated to analyzing and identifying the causes of destabilizing influences that the operator introduces when interacting with technical systems, as well as developing diagnostic approaches and optimizing these interactions.

Rationality in management and its deviations due to the human factor can significantly affect the stability and safety of navigation. An important aspect of the study is the development of effective diagnostics for decision-making chains by operators [4, 5], which can lead to an accumulation of destabilizing influences on ship systems at least in the long term. This implies a thorough in-depth analysis of the operator's decision-making processes and their consequences for the operation of technical systems.

The proposed approach consists of integrating automated and ergonomic systems with a focus on a two-stage interaction, where the operator plays a critical role as the central element of a dual system. The primary task of such integration is to determine the optimal phases of the operator's rational action to ensure the reliability and stability of ship technical systems in response to internal and external uncertainty.

Recognizing the importance of this task leads to the necessity of diagnosing the functionality of technical systems in an open-loop configuration, where the operator acts as a connecting link and exerts a direct influence on the management and operation processes of the vessel. The development of such diagnostic procedures requires a deep analysis of the interaction between the operator and ship systems, their operability, and decision-making in real operational conditions.

This class of problems represents a new direction in the comprehensive analysis of human-machine systems, where the integration of two types of control has the potential to significantly improve the quality of operational parameters and overall safety of navigation. The results of this study may find wide application in the design and management of maritime transport systems and facilities, and also contribute to the development of advanced methods for training operators to work in the complex and dynamic conditions of modern navigation.

**Presentation of the Main Material.** The research task thus arises to analyze approaches to identifying destabilizing influences from both the operator and automation tools, predict their operationalization levels at different stages of exploitation, and those that have complex control trajectories.

In the first phase of creating such a system, it is necessary to isolate the phases of the operator's activity in which a negative impact on the functionality of ship technical systems is observed, its character, and probable consequences in the long term. Based on the forecast indicators regarding the negative manifestation of the human-operator factor at individual stages of exploitation, complex maneuvering in dangerous navigation zones, execution of complicated operations, it is possible to obtain a conditional temporal map of negative impacts on marine technical systems and complexes (MTSC).

Meanwhile, practice indicates that the average percentage of maritime accidents related to the human factor from 2014 to 2020 amounts to 89.5% [6]. In the study for different types of

vessels, the following percentages were determined: cargo ships: 89.1%; fishing vessels: 89%; passenger ships: 89.1%; service vessels: 91.2%; other types of ships: 95.2%. However, to detect the causes of accidents and create formal models for their at least partial avoidance, the authors of the study developed a methodology of thorough analysis of contemporary literature aimed at analyzing the reliability of the human operator. Thus, a research procedure scheme was created that visualizes the hierarchical structure of information sources and categories used for the selection and analysis of over 100 scientific works.

Here is the scientific-style English translation of the given text:

Upper Level: International Maritime Organization (IMO), dissertations, journal articles, and conference materials. These sources are divided into categories that determine the content of the articles: human element, human factor, human error, and human reliability analysis.

Lower Level: Details the research methods in the context of the categories: definitions, state of research, discussion, comparison, and analysis.

The analysis performed allowed the authors to identify the following categories of errors:

Part A: Represents specific categories of errors that impact the safety and efficiency of vessel operation:

Errors in team management, planning, monitoring, and execution.

Planning errors and incorrect actions.

Insufficient reporting, verification, and non-compliant execution.

Perception, decision, and execution errors.

Human factor errors leading to hazards and unsafe actions.

Part B: Describes types of errors, which are divided into perception, decision, execution, individual errors, and team management errors. For each of these categories, a more detailed description is provided:

Perception Errors: include negligence, insufficient vigilance, excessive fatigue, etc.

Decision Errors: related to incorrect decision-making, lack of experience, and insufficient understanding of information.

Execution Errors: include insufficient reporting, flaws in checking, and failure to perform appropriate procedures.

Individual Errors: may be caused by alcohol, lack of training and education, stress, and unfamiliarity.

Team Management Errors: include planning, unreliable supervision, lack of communication, and coordination.

Despite the thorough analysis of operator errors, unfortunately, approaches for their automated identification and the prediction of impacts on MTSC are not described.

Other scholars have gone further in the matters of identification [7], attempting to determine the link between human factors and the safe operation of navigational service operators by means of Vessel Traffic Service (VTS).

As a result of the research, the authors identified a regulatory framework related to VTS, which is based on international norms, such as SOLAS Convention Regulation 12 of Chapter V, IMO Resolution A.1158(32), and IALA standards. These documents form the basis for recommendations, guidelines, and training courses that influence the qualifications and activities of VTS operators.

The authors point out the necessity of focusing on the human factor as a key element in supporting maritime safety. The regulatory structure and research methodology emphasize the importance of a systematic approach to studying and improving maritime traffic management practices. From this, a methodology was determined for calculating the staffing provision for VTS using such input data as the number of hours per day, number of working days, hours of training per year, etc., to determine the total number of staff required for operational efficiency of VTS.

An analysis of over 400 sources revealed that the key research keywords: "maritime shipping," "safety," "human factors," "risk assessment" have shifted the emphases of research over time, with a focus on "human error" and "risk assessment" in later works. Important elements of risk in the model proposed by the authors include interaction, fatigue, trust, and communication, which affect the performance and workload of the operator. Key changes between regulations A.857(20) and A.1158(32) have also been identified. The new regulations propose a less stringent and more flexible approach to VTS qualifications, taking into account the need to adapt to the rapid development of technologies and changing working conditions. The importance of conducting further research into VTS operator fatigue and their workload is noted, which is of great significance for ensuring maritime safety.

However, despite an even more detailed analysis, no recommendations or approaches were provided regarding the identification by artificial means of indicators that affect operator error during the operation of MTSC.

From the perspective of technical system reliability analysis, the authors of study [8] consider the comparison of two maintenance methods: scheduled and comprehensive predictive maintenance. A correlation between the frequency of scheduled maintenance ( $q$ ) and the probability and timeliness of failure prevention is established. It is evident that increasing the frequency of maintenance (decreasing  $\Delta t_{sch}$ ) improves the probability of preventing failures ( $P_{pre}$  and  $P_{sch}$ ), but it also increases the cost per unit of maintenance ( $w(t)$ ). This suggests that there is an optimal frequency of maintenance that minimizes the overall costs. In the paper, corresponding mathematical modeling is performed for scheduled maintenance with additional intermediate controls ( $\Delta t_{sch} = 0.9$ ). The researchers took a step towards integrating intermediate checks into the maintenance plan and highlighted the efficiency in optimizing the frequency of technical maintenance.

However, the approach to taking into account the forecast of the operator's actions, his errors in the operation of MTSC will allow a more qualitatively new level of approach to solving the problem of safety management of MTSC.

The authors of study [9] focus their attention on developing a methodology for determining logistics support needs based on the Mean Time To Failure (MTTF) indicator. Using MTTF as a key indicator can significantly influence decisions regarding logistical planning, providing more accurate forecasting of needs for spare parts and maintenance. The main focus of the study is on predicting failures that may potentially occur during the planning period and methods for calculating the MTTF. Various statistical distributions are used to model the reliability of systems and components, including normal, exponential, Weibull, and log-normal distributions. It was determined: trends in MTTF, namely the change in annual MTTF (average time to failure); reliability functions and histograms (probability densities and failure histograms for three different objects); MTTF analysis and failure distribution (comparing experimental MTTF data with MTTF estimates according to different statistical distributions).

However, the study did not take into account the peculiarities of operation, emergency transitions to engine operating modes, incorrect operator actions that accelerate wear and breakage of MTSC during errors in management actions.

At the second stage, there is a need to analyze the capability of existing automation tools to perform control operations without operator intervention for certain time intervals during the execution of individual control operations for MTSC.

In work [10], the issue of testing these models of the probability of fault-free performance (FFTP) for homogeneity, the probability of anomalies or random outliers is investigated. To verify this, appropriate statistical models and criteria based on Bayesian methods and distributions were created to assess the reliability of RTC systems by calculating FFTP. The authors also discuss establishing confidence limits for FFTP estimates, a step that involves determining the probable range in which the true value of system reliability lies. This is significant for making informed decisions about the operation and maintenance of RTC systems.

Interestingly, operational decisions are analyzed, that is, the consequences of these estimates, suggesting that the models can influence decisions related to the control and assessment of RTC systems in accordance with confidence intervals and posterior densities for FFTP. Simulations of RTC reliability change processes based on technical specifications and their evaluation using a combined method have been carried out. Thus, the link between the technical system of identifying the technical condition and the operator, who relies on sensor indicators and automatic equipment, is traced. However, the algorithms for interaction and formal methods for processing such information to make adequate management decisions are not specified.

In the study dedicated to assessing the sensitivity of a system's failure probability to deterministic inputs [11], the primary focus is placed on Local Sensitivity Analysis (LSA) methods. The paper describes reliability-based design optimization approaches and the impact of deterministic parameters on the system's failure probability.

The human factor in this research is considered within the reliability model as an element that may influence the probabilities of failure due to operational errors, maintenance procedures, human decision-making, or other aspects of human-system interaction. In the context of this article, the human factor is implicitly regarded as one of the potential deterministic inputs that affect random inputs or functions in the reliability model, only in this instance it becomes part of the sensitivity analysis of the system.

However, numerous mathematical calculations have been performed, which allowed to: determine the variability and mean square error (MSE) of sensitivity estimates of failure probability relative to parameters  $\theta$ ; conduct Monte Carlo simulations to assess variability, highlighting the advantages of resampling through the derivation of probabilities with respect to  $\theta$  and computing expectations considering the assessment function; execute local sensitivity analysis and the use of standard normal space for input variables; compute the mean square error associated with different sampling methods; carry out FORM and SORM approximations by approximating the derivatives of failure probabilities with respect to distribution parameters; apply the Multi-Hyperplane Combination Method (MHCM), Directional Sampling (DS), and Linear Sampling (LS) methods for assessing the sensitivity of failure probability, where each method has its own set of equations and logic for calculations.

Nevertheless, the authors conclude by proposing a so-called "Weak Approach" for sensitivity analysis in the context of engineering probabilistic assessments when surface integrals, necessary for sensitivity analysis, cannot be directly calculated using Monte Carlo methods. Based on this approach, an approximation method for the indicator function used in reliability engineering is created to facilitate sensitivity analysis, which is proven by indicators of standard deviation,  $\sigma$ .

In the context of both the design and operation of the specified systems, the manifestation of a negative operator factor is possible: during data collection (unconscious selective perception of data, where engineers or analysts focus only on information that confirms their prior assumptions); in model selection (choosing an inadequate indicator function that does not reflect the real behavior of the system); during analysis (incorrect application of statistical methods, such as a wrong definition of the magnitude of  $\sigma$ , which can be related to insufficient qualifications or errors in conclusions); in the interpretation of results (subjective interpretation of results, where analysts may be prone to favoring outcomes that match their expectations; insufficient or excessive optimization of safety measures due to misconceptions about the real probability of failures, etc.).

In this regard, the operator is also an intermediary link in the verification of the main model settings and indicators, whose requirements for objective action are sufficiently high and determinative in the subsequent operation of MTSC.

If we examine study [12], which focuses on breakdowns down to purely technical aspects of the operation of unit elements, parts, structural components, then even in the early period of

operation, the analysis of failures of technical and energy components of systems shows a negative operator factor of MTSC. The authors have investigated a broad spectrum of main causes of malfunctions, such as structural defects, manufacturing errors, operational errors, external factors, and aging factors. A classification of malfunctions depending on the type of destructive processes, which include mechanical, chemical, electrical, or thermal, is also discussed.

Observations of malfunctions during the first year of operation of a bulk carrier allowed for a thorough analysis of component failures, their causes, time to failure, and methods of recovery or repair, where failures ranged from leaks in mechanical seals to cracks in mechanical components and electrical overloads. Algorithms for failure identification, replacement of damaged parts, and repair processes that have been carried out to restore functionality, which are valuable for marine engineers, repair crews, and other professionals involved in operation and safety management, are provided.

However, it should be noted that three aspects of failures have been identified: wear and tear of MTSC components (49%); operator factor in failures - operator errors account for 19% of all failures; pump equipment failures (33%).

This data highlights the importance of focusing not only on improving materials and designs to combat equipment wear and technical failures, but also on the necessity to reduce the number of operator errors.

Interesting in the context of the mentioned problem is the research [13], which focuses on the identification of intentional attacks and technical malfunctions in cyber-physical systems, with a special emphasis on the water resource management sector. The paper describes a methodology for deriving expert knowledge and probabilistic reasoning using Bayesian networks (BNs) to model and analyze risks. Thus, the authors analyzed factors that contribute to sensor errors, such as the lack of physical maintenance, poorly written maintenance procedures, weak physical access control, and failure to perform sensor data integrity verification. These factors are taken into account when assessing the likelihood of sensor errors leading to incorrect water level measurements, for example.

In particular, a Tornado diagram was used, which approximates a sensitivity analysis in the form of ranks of the impact of various causes on the likelihood of the main cause of sensor errors. It underscores that the lack of physical maintenance, poorly described operating procedures, and weak physical access control are significant factors.

A significant portion of the article focuses on deriving expert knowledge and using performance-based assessment to ensure the accuracy of the obtained parameters, thanks to which the authors propose a decision support system to assist the operators of cyber-physical systems. According to the modeling results, the sensitivity range for the cause "Lack of physical maintenance" was recorded in the intervals 0.139009 – 0.184037, compared to the central value of 0.157056.

This fact once again confirms the relevance of the above considerations and necessitates the development of a system for identifying destabilizing factors of operators in the management of cyber-physical systems.

One of the approaches to reducing risks in the management of cyber-physical systems is the creation of decision support systems. An example of such an approach is the study [14], which utilizes concepts of semi-Markov processes, quality space, and multi-objective analysis for the operation of the most critical technical systems.

In modeling, random time intervals between state transitions were assumed, where maintenance activities do not follow an exponential distribution of time, with transition probabilities depending only on the time interval since the last transition. The research presents a matrix equation to determine the limiting probabilities in a Markov chain, which includes normalization to ensure that the sum of probabilities equals 1, resulting in a system of linear equations that can be solved to find the stationary state probabilities of the system.

A mathematical model has been developed to evaluate the quality of work of "human-machine-environment" (HME) systems, where the working quality of each function has an area defined by boundary values, and within these limits, there are subdomains corresponding to different quality levels: undesirable, recommended, restricted, acceptable, and desired quality. The MAXSIMP criterion, similar to MAXINV but with a different calculation of the degree of fulfillment, was proposed to replicate the overall operational quality, which can be expressed as the total degree of all levels of criteria fulfillment, with an equation provided for this calculation.

Following these approaches, an expert system was developed based on multi-criteria decision-making methods that determine the state of technical maintenance and operational processes, represented by a directed graph. The system models technical maintenance and operational processes, and thanks to its application, a strategy for functional maintenance is selected that ensures the execution of operations with quality above the critical level.

However, the study indicates that the construction of a quality management system for the operation of transport technical systems depends on expert considerations, whose opinion can significantly influence the adoption of a management strategy and add uncertainty already at the first stage of system design.

**Conclusion.** As previously noted, the human operator factor within MTSC in a general sense possesses a complex system of influences, further compounded by individual information perception [15-17], which significantly complicates the process of predicting their actions. Despite this, current technologies are still unable to transition to fully autonomous maritime transport due to an insufficiently developed system for identifying both external and internal risk factors under conditions of uncertainty.

The thesis presents a review of research which investigates the interaction between human operations and automated control systems, playing a pivotal role in the safety and efficiency of navigation. It is observed that despite advancements in automation, the human factor remains one of the most unpredictable elements in the management of MTSC. It is identified that errors made by operators can substantially impact the stability and safety of navigation, leading to the destabilization of ship control systems.

An integration of automated and ergonomic systems is proposed with a focus on a two-tiered interaction, where the operator plays a key role as the central element of the dual system. The importance of reliability and timely response to internal and external uncertainties in the management of MTSC is emphasized. There is a detailed consideration of the importance of diagnosing the functionality of technical systems in an open loop, where the operator acts as a connecting link that directly influences management processes and decision-making in real operational conditions.

A core part of the study is the analysis of approaches to identifying destabilizing influences and key materials dedicated to exploring ways of identifying and predicting the levels of technical system operations under various conditions. Through analyzing types of errors, a differentiation is made into perception errors, decision-making errors, execution errors, individual errors, and team management errors, each of which is described in detail.

Based on these studies and the analysis of incidents related to system malfunctions, the conclusion is drawn that to improve the reliability and safety of managing MTSC, the focus must not only be on technical aspects but also on human and organizational factors. This implies the development of effective decision-support systems for operators, continuous improvement of control system ergonomics, and rational management taking into account the human operator factor in MTSC.

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