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Navigational safety assessment based on Markov-Model approach

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ABSTRACT

Safety analysis of complex technical systems currently operating in the transport sector is an urgent challenge for the global maritime industry, which suffers from a lack of information about the levels of risk and the consequences of their incorrect assessment. Among the requirements for vessel management and operations the importance of having a highly professional crew and up-to-date navigational equipment. Navigational safety is one of the components of the integral concept of "safety" for a seagoing ship. Assessment of integral safety is based on assessments of the individual safety components. In this study, the focus is on "navigational safety", which is primarily understood as ensuring safe operation of a vessel in specific navigation conditions, ensuring safe control and maneuvering of the vessel, ship position monitoring, heading control, sufficient depth margin under the keel along the route, taking into account its actual draft and subsidence in shallow water, and sea disturbance. In the offered research on the basis of the identified states of navigational safety, the graphic model of process and matrix of transition probabilities in the general form with use of homogeneous Markov model of change of navigational safety of a vessel, with discrete time and presence of absorbing state is formed. The proposed Markov process model can be used to assess vessel navigational safety when establishing possible states of navigational safety with significant probability to assess ship safety and make decisions to ensure safe vessel operation.

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1 Introduction

Safety is one of the key requirements of modern shipping (ISM Code, 1997; STCW, 2001) and includes a variety of components, one of which is navigational safety, measures of which are prescribed in (SOLAS,74). At the same time, the lack of navigational safety can lead not only to serious material losses, threat to life of crew members, but also to significant environmental damage (Statistical summary, 2021). Thus, the following works are devoted to methods of risk assessment in the process of ship operation, such as risk modelling for passages and port approaches, risk assessment and analysis in maritime transportation is considered (Smolarek and Sniegocki, 2013; Wang et al., 2020; Guze and Kołowrocki, 2017). An integrated risk assessment model for safe Arctic navigation is studied in (Znang et al., 2020) which is a specific example of risk assessment for a ship in non-standard sailing conditions.

Issues of integrated safety of oversized and heavy cargo transportation and their impact on the safety of the ship are presented in (Onyshchenko and Melnyk, 2020), where the ship is conceptualized as six major technical subsystems, each of which has an impact on safety. At the same time, each subsystem, including navigational subsystem, can be in operational or non-operational state, which integrally forms the state of the vessel in terms of safety as a set of states of its individual subsystems. Nevertheless, each of the components of navigation safety can be considered in more detail, as it is formed, in turn, from the totality of states of each component of ship subsystems. This will enable a more in-depth study of the changes in the state of each subsystem, more clearly identify possible risks, problems and ways to solve them (Dziula et al., 2007; Faghih-Roohi et al., 2014; Celik et al., 2010).

In (Onyshchenko et al., 2021), the operational state of a vessel and efficiency of ship operation in transportation of oversized and heavy cargo by optimizing the speed mode considering the impact of weather conditions is reviewed. Modeling and optimization algorithms in ship weather routing is studied in (Walter et al., 2016). Methods for collision and grounding avoidance and traffic accident prevention is proposed in (Ahmed et al., 2021; Van de Weil and Van Dorp, 2011; Haenninen, 2014). Risk-based system to control safety level of flooded passenger ships is considered (Trincas et al., 2017). A new method for assessing the safety of ships damaged by grounding is researched (Paik et al., 2021), which makes it possible to assess the level of safety of ship operation, taking into account the impact of weather conditions and the integrity of the ship's hull.

It should be noted that the problems of navigation safety are directly related to navigation issues and standards of efficiency of ship navigation and radio communication equipment, which practically do not fall into the focus of modern research. However, it is noteworthy that some works are devoted to this issue are (Titlyanov et al., 2008; Rokseth et al., 2017; Gucma, 2000). However, as a rule, most of them are related to the issues of navigational safety without modeling of the changing states of the navigation complex under failure conditions.

The most appropriate mathematical apparatus for assessing the state of a technical object is Markov process theory are (Gilter, 2013; Peel and Good, 2011; Kana and Droste, 2019; Jaskolski, 2011). In particular, based on this apparatus, various problems related to shipping, including safety of navigation, have been solved. Method of prompt evasive maneuver selection to alter ship's course or speed as part of navigational safety issues is studied in (Burmaka et.al., 2021). Safety of autonomous ships steering process control is evaluated in (Melnyk et al., 2022), which characterizes the use of different models and methods in ensuring the safety of ship operations.

This study focuses on the problem of navigational safety of a vessel and considers it in the context of the state of its navigation complex, among which: ensuring navigational safety using on-board gauges and systems, maneuvering and divergence with targets using the ship's motion control system; providing communications for safety; and assessing the hydrometeorological situation. Thus, the aim of the study is to assess the navigational safety of the ship based on the simulation of changes in the states of the navigation complex.

2 Materials and Methods

2.1 Navigation-related accidents overview

The problem of navigation safety became especially acute from ship grounding and collisions at the beginning of the last century due to the increase of navigation intensity. In response to spontaneous growth of merchant fleet accident's rate, international organizations such as International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), International Maritime Organization (IMO) and others regulating all-important aspects of accident-free navigation were established. The objectives of the ISM Code (International Safety Management Code) is to ensure maritime safety by prevention of human injury or loss of life, avoidance of damage to the environment, in particular, to the marine environment, and to property (Fig. 1).

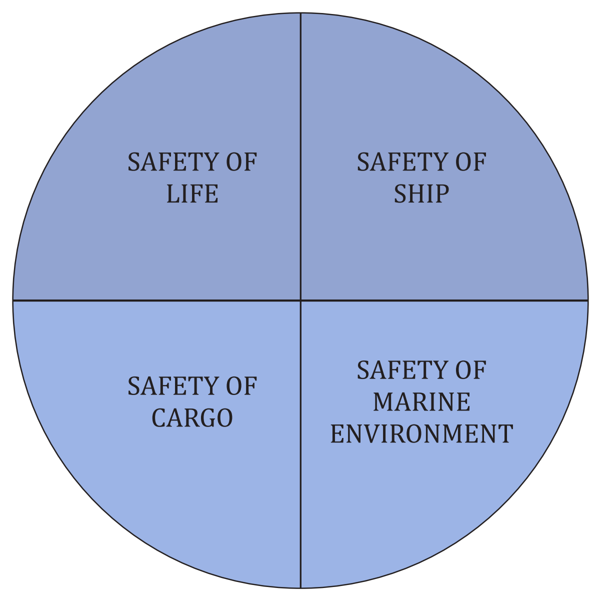

Fig. 1 Main objectives of ISM Code

Source: Authors

With the exception of the structural components of ship safety, the concept of "navigational safety" narrows the scope of this concept only to issues of purely navigational nature, i.e. ship handling and maneuvering, information acquisition and processing during the voyage, determination and control of her position.

According to the fleet accident statistics of the last decade, the following were among the dominant ones as a result of navigational safety violations:

- Collision;
- Grounding or touching ground;
- Fire and explosion.

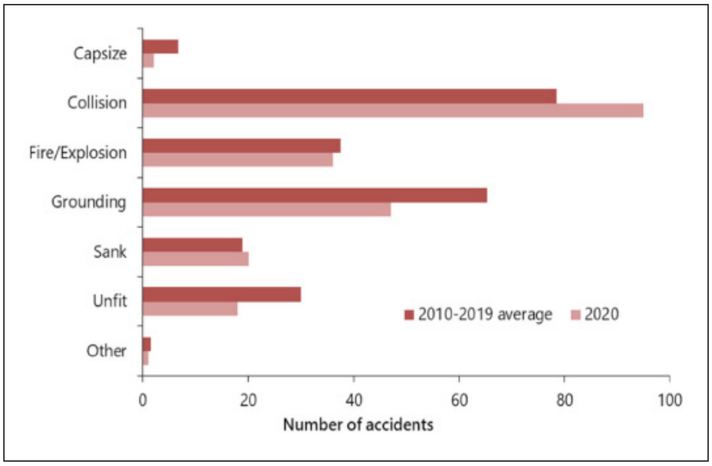

Fig. 2 Shipping accidents, by accident type, in 2020 compared with the 2010–2019 average

Source: [26]

Overview of accidents and casualties shows that during 2020, 262 marine accidents were reported, down from the 2019 total of 267 and below the 10-year (2010–2019) average of 289 (Fig. 1). In 2020, the proportion of shipping accidents (as opposed to accidents aboard ship) was 84% of marine accidents, comparable to the previous 10-year average of 82%. There were 219 shipping accidents in 2020, up from the 2019 total of 207 but down 8% from the 2010–2019 average of 238 (Statistical summary, 2020).

As shown in Fig. 2, a comparison of the 10-year period with accident rates for 2020 alone is shown. The most frequent types of shipping accidents in 2020 were collision (43%), grounding (21%) and fire/explosion (16%). The total number of collisions (95), which was 21% higher than the 10-year average (2010-2019) of 79 cases, the number of groundings (47), which was 28% lower than the 10-year average (65), and the number of fire and explosion accidents (36), which was 4% lower than the 10-year average (37). Statistics show that the vast majority (82%) of reported incidents involved complete failure of any equipment or technical system (Fig. 3).

Regarding the types of vessels that were most frequently involved in complete failure of any equipment or technical system in 2020 were fishing vessels (52%) and dry cargo vessels (25%). Therefore, research aimed at as-

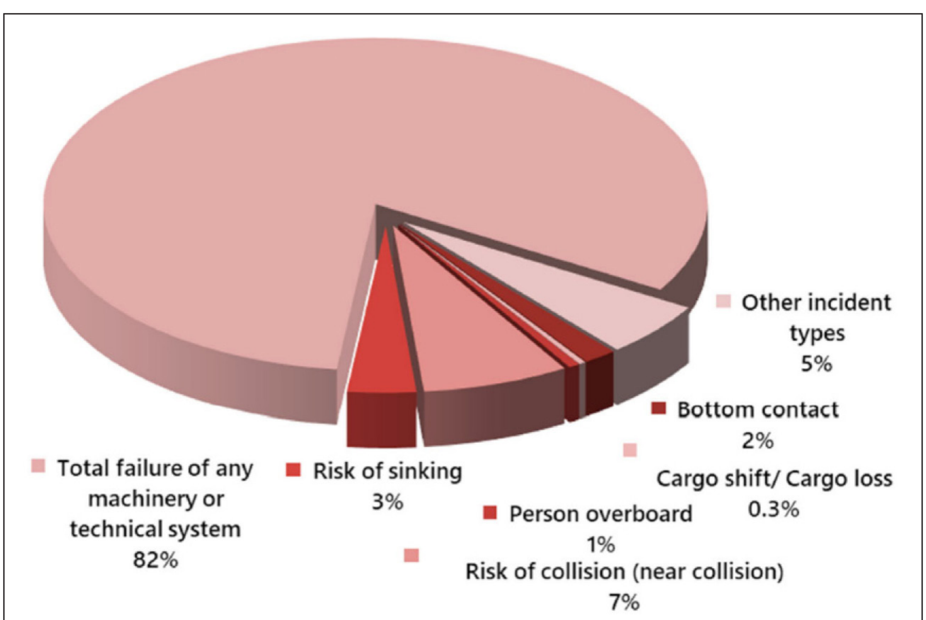

Fig. 3 Marine incidents, by type, 2020

Source: [26]

sessing the reliability of equipment under operating conditions, as well as methods to ensure the performance quality of on-board equipment among the issues that are characterized by a high degree of relevance.

2.2 Ship navigation complex concept

The process of combining various ship automated systems into a set of devices, which includes various configurations of such systems, providing the process of navigation and ensuring integration of navigation processes, is called navigation and information complexes. Such complexes serve both as an information support system for the navigator's decisions and as a system that ensures the coordinated operation of the lower hierarchy of the ship's automated systems. The navigation complex should be understood as a combination of onboard measuring and indicating systems, communication and safety systems, ship motion control, handling and maneuvering systems, which enable to operate the ship, monitor her position and speed as well as maintain assigned course. The tasks to be performed by the navigation complex are multiple, but one of the most important among them is to ensure comprehensive safe operation of the vessel. It is a multi-component electronic system designed for maintaining optimum parameters during navigation. The accuracy of navigation calculations is the responsibility of the ship's navigation complex, which consists of:

- Shipboard technical aids of navigation and communication;
- Shipboard equipment for ship handling control tasks.

Trouble-free functioning of the relevant navigation complex, which is formed of three basic components, ensures the navigational safety of a vessel proposed in this study. Thus, the research of navigational safety and the modelling of changes in its state is based on the analysis of states variation of the navigation complex (Fig. 4).

Conventionally, the complex can be divided into three main elements: measuring system, communication safety system, and ship control system.

Within each of the systems, the following functions are performed:

1. Ship navigation and motion parameters indicating system is a system for obtaining operational information during the process of navigation, which includes various information sensors and devices such as speed measuring and under keel clearance (log, echo sounder), course indications (compasses), radar equipment and systems, satellite navigation and positioning equipment. Marine radar systems, electronic navigation instruments that allows obtaining information about current ship position, its movement parameters with respect to the specified route.
2. The communication and safety system includes shipboard equipment designed to obtain essential safety information to support navigation, precautions about possible hazards and changing conditions along the passage route, keeping charts and publications up to date, transmitting messages and conducting radio conversations related to navigational safety.
3. Propulsion control system, which implements the functions of ship operation providing the change of her kinematic parameters. It also includes ship's course steering system, remote power plant control system and remote operation of machinery and automation systems.

2.3 A Markov process model of the variation of navigational safety states

Each component of the navigation complex can be in one of two states – operational or non-operational. The non-operational state of each technical component of the complex is caused by various reasons, which in general can be represented as follows: dangerous rolling, weather phenomena, structural damage, ground contact, technical

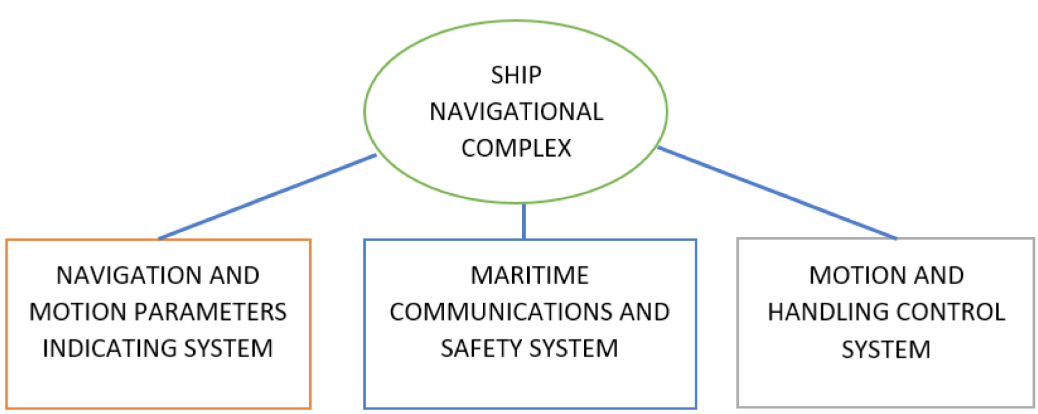

Fig. 4 Navigation complex basic components

Source: Authors

reasons, moral and physical wear and tear, equipment failure and human factor.

Consider that the failure of components of the navigation system is permanent in nature – physical damage requiring repair or replacement, etc. Therefore, it is possible to return to working condition only after certain actions of the crew. Nonetheless, it is not always possible to replace and repair navigational equipment during ship's voyage. Therefore, at this stage of research we examine a situation when repair or replacement of navigational equipment during the voyage is not provided.

The analysis of specificity of navigational safety of a vessel allows identifying its six basic states where the values are assigned on the expert evaluations, based on author's professional experience and the logical sequence of possible ship states in a given situation. To identify the main six states of the object under study «navigation complex» consisting of three main systems, it is proposed to decompose the specified state into two variants (normal – problem) according to the three components: «Motion and handling control system», «Navigation and motion parameters indicating system», «Ship's communication and safety system». Such an approach is determined, first, by the specifics of ship operation, which is reflected, for example, in the peculiarities of the equipment. This, accordingly, can lead to certain violations during the ship's voyage. Positive («normal» – 1) and negative (« having problems» – 0) evaluations of each component form the following classification of main ship's condition states as well as the resulting «Ship's condition with regard to navigational safety» (Table 1).

Let us denote 1 – the working state of the component of the navigation complex, 0 – the non-working state. Thus, the variation of states of the navigation complex as a whole can be represented as follows (Fig. 5). The components of the navigation complex are independent, and their transition to the inoperative state is also independent of the other components.

The first position in the complex in Fig. 5 is the measuring and indicating system, the second is the communication and safety system, and the third is the ship's motion control system. Variation of states of the navigation complex forms a Markov chain. Indeed, the process under consideration has "Markov property", that is, the current state of the complex depends only on the state the complex was in before. In addition, transition to the next state is determined only by the current state of the complex. This random process of changing states of the navigation complex is classified as homogeneous, with discrete states and discrete time.

The discreteness of time is taken into account that the process of vessel operation (voyage performance) is usually considered with discrete time – hours, days. The "step" during which the transition from state to state takes place can be taken as 24 hours (1 day). Naturally, it can be reduced depend on specific information about the voyage duration. Given the universality of the approach for merchant ships of various sizes, including those operating short trips, a daily «step» is appropriate. Therefore, such accounting of time is adopted in this study.

Navigation complex can remain in each state for quite a long time. The state of complete failure of the navigation complex (0,0,0) is absorbing, i.e. in this state the navigation complex remains until repairmen or some parts replacement. The graphical model of Markov process (Fig. 5) reflects the ways of transition from fully operational state of three components of the complex to non-operational state of fully non-operational navigation complex (which,

Table 1 Basic states of ship's navigational safety according to the state of components of navigational complex

State	Motion and handling control system	Navigation and motion parameters indicating system	Ship's communication and safety system	Ship's condition with regard to navigational safety
C1	1	1	1	Navigation safety satisfactory
C2	1	1	0	Maintaining motion parameters without communication and safety equipment
C3	1	0	0	Maintaining motion and handling characteristics without information about its parameters and means of communication and safety
C4	1	0	1	Maintaining motion parameters without the performance of the steering control systems
C5	0	1	1	A vessel not under command with operable indicating and communication systems
	0	0	1	
	0	1	0	
C6	0	0	0	Ship's emergency status and loss of navigational safety

Source: Authors

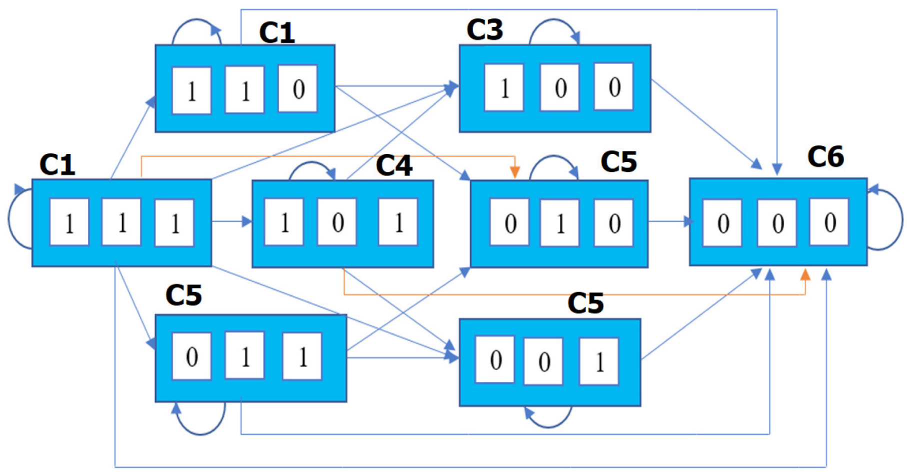

Fig. 5 State changes of the navigation complex

Source: Authors

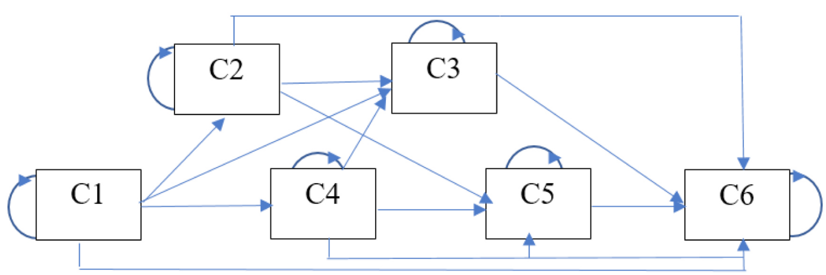

Fig. 6 The graph of changes in the ship's navigational safety status

Source: Authors

it should be noted, has a very low probability, nevertheless, it cannot be ignored when it comes to safety in any context).

From one state to another, the navigation complex transfers in accordance with the transition probability matrix. Transition probability values for each ship are determined statistically or by expert method taking into account specific technical state of navigation complex components. In the absence of the necessary amount of statistical data, experts estimate probabilities taking into account the technical features of the equipment and its operating conditions.

This model describes the variation of navigation complex states of the seagoing vessel, which determine the state of ship's navigational safety. Thus, the process of the navigation complex states variation determines the process of states variation of navigational safety of the vessel. Such decomposition of processes is necessary by the reason that not every of eight states of navigation complex defines a separate state of navigational safety.

Changes in these states also form a Markov process, because changes in the navigation safety states are based on changes in the state of the navigation complex (Fig. 6).

A matrix of transient probabilities for the process of navigational safety change is generated based on the matrix of transient probabilities for the process of navigational safety change:

$$P = \left[p_{ij} \right] = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} \\ 0 & p_{22} & p_{23} & 0 & p_{25} & p_{26} \\ 0 & 0 & p_{33} & 0 & 0 & p_{36} \\ 0 & 0 & p_{43} & p_{44} & p_{45} & p_{46} \\ 0 & 0 & 0 & 0 & p_{55} & p_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \qquad (1)$$

where $0 \le p_{ij} \le 1, i = \overline{1,6}, j = \overline{1,6}$, in addition $\sum_{j=1}^{6} p_{ij} = 1, i = \overline{1,6}.$

A complete mathematical description of this process involves specifying the initial probabilities $p_1(0)$, $p_2(0)$, $p_3(0)$, $p_4(0)$, $p_5(0)$, $p_6(0)$, that is, the probabilities of the navigation safety state at time t = 0, which satisfy the condition:

$$p_1(0) + p_2(0) + p_3(0) + p_4(0) + p_5(0) + p_6(0) = 1. \qquad (2)$$

The Kolmogorov-Chepman relations (3) allow us to determine the probabilities of different states of navigational safety of the vessel at subsequent moments of time:

$$p_j(t) = \sum_{i=1}^{n} p_j(t-1) \cdot p_{ij}, j = \overline{1,n}, t = 1,2,3,.. \quad (3)$$

Having known the duration of the upcoming voyage $t = T$, we can calculate the probabilities of navigational safety states for this moment in time. Naturally, navigational safety is only one component of vessel safety (see Fig. 1). However, the assessment of navigational safety will allow, along with assessments of other aspects of safety, to evaluate the safety of a particular vessel in a particular voyage.

2.4 Navigational safety assessment calculation

To illustrate the proposed approach, we take the following transition probability matrix:

$$P = \left[p_{ij}\right] = \begin{bmatrix} 0,99 & 0,008094 & 0,001 & 0,0009 & 0,000005 & 0,000001 \\ 0 & 0,99 & 0,0099 & 0 & 0,000095 & 0,000005 \\ 0 & 0 & 0,99991 & 0 & 0 & 0,00009 \\ 0 & 0 & 0,0009 & 0,99 & 0,00909 & 0,0001 \\ 0 & 0 & 0 & 0 & 0,99 & 0,01 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (4)$$

Suppose we consider a short voyage (short passage) $T = 5$ days. The initial state of the ship's navigational safety is estimated as:

$P_1(0)=1; P_2(0)=0; P_3(0)=0; P_4(0)=0; P_5(0)=0; P_6(0)=0,$

These probabilities reflect operable state of all components of navigation complex with single probability. For the fifth "step" (i.e. at the moment of the end of the ship's transition from port to port) the transition matrix has the form:

$$(P)^4 = \begin{bmatrix} 0,9606 & 0,03141 & 0,00442 & 0,00349 & 0,00007 & 0,00001 \\ 0 & 0,96060 & 0,03900 & 0 & 0,00037 & 0,00003 \\ 0 & 0 & 0,99964 & 0 & 0 & 0,00036 \\ 0 & 0 & 0,00355 & 0,96060 & 0,03528 & 0,00058 \\ 0 & 0 & 0 & 0 & 0,96060 & 0,03940 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5)$$

and the probabilities of the transition states of ship's navigational safety are estimated as:

$P_1(5)=0,9606; P_2(5)=0,0314; P_3(5)=0,0044; P_4(5)=0,0035;$
$P_5(5)=0,000072; P_6(5)=0,0000054.$

It is obvious that with single probability of navigation complex working condition at the beginning of voyage and for short voyage (5 days), failure potential of one of the components of navigation complex (i.e. indicating, communication and motion control systems) and transition of state ship's of navigational safety to another from completely safe state has insignificant possibility. In particular, state C2 is possible with probability 0.03.

For a longer voyage with duration T=21 days and a less optimistic estimate of the initial state of ship's navigational safety:

$P_1(0)=0,99; P_2(0)=0,01; P_3(0)=0; P_4(0)=0; P_5(0)=0; P_6(0)=0,$

the transition ship's navigational safety state probability matrix has the form:

$$(P)^{20} = \begin{bmatrix} 0,8179 & 0,1337 & 0,01545 & 0,01487 & 0,001501 & 0,000126 \\ 0 & 0,8179 & 0,1801 & 0 & 0,001569 & 0,000267 \\ 0 & 0 & 0,9982 & 0 & 0 & 0,00018 \\ 0 & 0 & 0,01637 & 0,8179 & 0,15019 & 0,015508 \\ 0 & 0 & 0 & 0 & 0,8179 & 0,1821 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (6)$$

and probabilities of states of ship's navigational safety

$P_1(21) = 0,8097; P_2(21) = 0,1405; P_3(21) = 0,017;$
$P_4(21) = 0,0147; P_5(21) = 0,0015; P_6(21) = 0,000127.$

For the same voyage duration T=21 days, but with initial probabilities

$P_1(0) = 0,985; P_2(0) = 0,01; P_3(0) = 0,05; P_4(0) = 0;$
$P_5(0) = 0; P_6(0) = 0,$

probabilities of states of ship's navigational safety are:

$P_1(21) = 0,8056; P_2(21) = 0,1398; P_3(21) = 0,022;$
$P_4(21) = 0,01464; P_5(21) = 0,001494; P_6(21) = 0,000127.$

Thus, the probabilities of ship's navigational safety states C2 and C3 increase. Graphic illustration of probabilities of states is presented in Fig. 7.

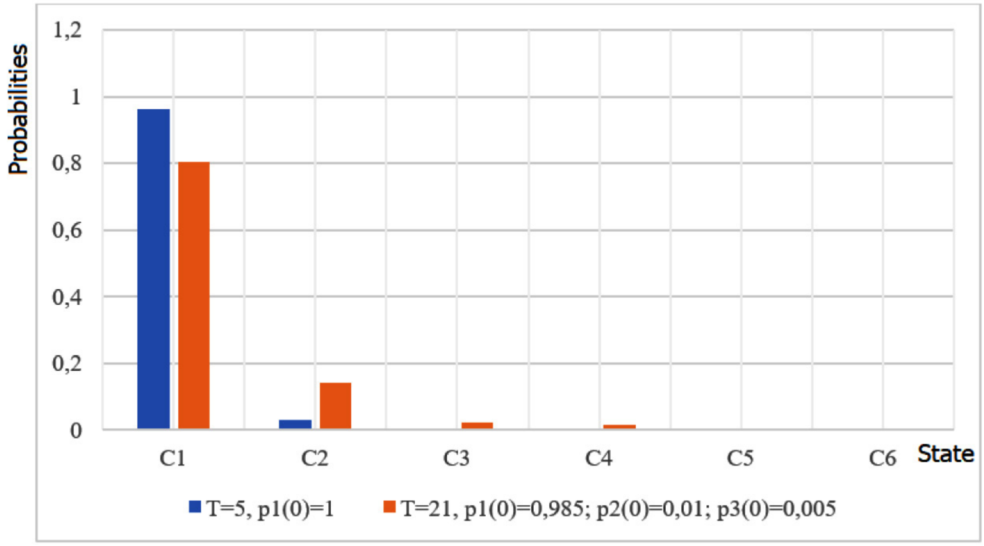

Fig. 7 Probabilities of ship's navigational safety states for different voyage duration and initial probabilities

Source: Authors

According to widespread sea practice as a rule short voyages on duration of vessel connected with insignificant risk of breakdown of navigational equipment, on this fact study was initially constructed. Also influence of weather conditions on degree of serviceability and reliability of ship equipment is minimized that characterizes a degree of display of a condition of a vessel C1 on small passages of a vessel.

3 Results and Discussions

As calculation results show, navigational safety for short voyages is evaluated as "normal" (probability 0.96), but for longer voyages and possibility of C2 and C3 states at the initial moment (when the ship has departed) navigational safety can be characterized as "satisfactory" (probability 0.8) and C2-C4 states have more significant probability (0.14; 0.022; 0.02 respectively).

At the present time, there is no scale for evaluating navigational safety in the context of "normal", "satisfactory", "unsatisfactory". Therefore, in formulating conclusions on the results of calculations, the approach was taken, according to which the probability above 0.95 for state C1 is the limit of "normal"; the probability of states C2-C6 above 0.05 is already "significant" (as accepted in risk theory). Therefore, depending on their combination, based on common sense and the logic of risk assessment, conclusions can be made about the predicted state of navigational safety in the voyage.

In order to determine the possible occurrence of any negative situations during the performance of ship operations, it is necessary to evaluate reliable and reasonable characteristics of risk in relation to the available opportunities and to determine a list of effective measures to reduce risks. For example, in order to improve safety of ship operation while maneuvering both in port waters and sailing in the open sea, each company develops organizational and technical measures, which include procedures for preparation of the ship for sailing in different conditions, under different visibility conditions, entering/leaving ports, in stormy weather, on boarding and disembarking a pilot, changing over navigational watch, performing cargo and mooring operations. This demonstrates that the probability of an emergency situation with negative consequences always exists, even the probability of its occurrence is considerably low. An example is mooring lines, which are used to secure a vessel at a berth. During cargo operations, mooring lines accumulate stress and usually break unpredictably when not expected. This once again emphasizes the stochastic nature of the process and the lack of predictability of the results. Therefore, the greatest danger is to use this system and reduce safety monitoring whenever results are «normal» or «satisfactory,» and to be cautious only when results are «unsatisfactory,» indicating that discrete approaches are useful for understanding the process, but not entirely successful in risk management.

4 Conclusion

Navigational safety of a vessel is formed as a result of the state of the navigation complex, which consists of three basic components. As any technical system, the components of navigation complex can be in either working or non-working state. In this research it is proved that the variation of states of navigation complex is Markov process, the graphic model of this process is obtained. The variation of states of navigation complex causes the variation of states of navigational safety of the vessel which is also the Markov process. In the given research six states of navigational safety are identified, the graphic model of process and matrix of transitive probabilities in the general form are generated. The Markov process of changing the navigational safety of a vessel is classified as homogeneous, with discrete time and the presence of an absorbing state. Therefore, the proposed Markov process model can be used to assess the navigational safety of a particular vessel on a particular voyage. In case of identification of possible states of navigational safety with significant probability, which cause concerns, adequate measures can be taken in advance, for example, provision of necessary spare parts for repair and replacement of navigation complex components on board the vessel.

The use of the proposed model is demonstrated on the calculation example for different voyage periods and initial probabilities. Calculations have shown efficiency and applicability for the given purpose of the given model, the formulated conclusions are an example for an estimation of navigational safety in practice of ship operation.

It is necessary to note, that such approach to an assessment of navigational safety is proposed firstly, and, unlike existing approaches to an assessment of safety of a vessel is based on decomposition to level of the specific technical equipment on a vessel, in this case a navigational component. Such an approach can be extended to other technical systems of a vessel to form a final model for assessing vessel safety.

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Author Contributions: Oleksiy Melnyk – conceptualization, methodology, data collection, research, writing, review and editing, supervision, validation, verification; Svitlana Onyshchenko – data curation, formal analyzes, verification, research, mathematical harmonization.

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