
CHAPTER 3

Consideration and assessment of navigational risks to improve energy-efficient ship management

Olena Rossomakha

Abstract

The section reveals the relationship between energy efficiency of shipping and navigational safety, which is of particular relevance in the context of the implementation of strict international environmental regulations (EEDI, EEXI, CII) and the growing requirements for optimizing fuel consumption. It is determined that classical methods of energy saving, in particular, reducing the speed, cannot be considered in isolation from the risks associated with the operation of a ship in difficult navigational conditions – narrow straits, areas of high traffic or unstable hydrometeorology.

The aim of the study is to develop an integrated approach to ship management that simultaneously takes into account energy efficiency and navigation risks. For the first time, the expediency of using multi-criteria routing models based on fuel consumption, accident risk, and current hydrometeorological conditions is substantiated. The article presents decision-making algorithms taking into account navigation safety constraints, which allow to adapt management actions in real time.

IMO requirements for fleet energy efficiency are outlined, as well as ways to implement them both technically and operationally. The role of digital solutions, including ECDIS, DSS, NAPA, StormGeo, Wärtsilä Voyage platforms, which support the crew in making informed decisions during the voyage, is emphasized. Particular attention is paid to the use of artificial intelligence methods for risk forecasting based on large amounts of data.

The article systemizes the classification of navigation risks (technical, human, digital, environmental), as well as methods of their assessment: qualitative (FMEA, SWOT, HAZID) and quantitative (ETA, FTA, risk matrices). The article considers the formation of an integrated hazard map, which includes trajectory points of the ship's route, maneuvering characteristics, weather forecasts, the state of equipment and crew training. It is shown that the combination of digital platforms, mathematical modelling and engineering analysis ensures informed decision-making.

An approach to building a decision support system is proposed, taking into account changes in the external environment, technical characteristics of the vessel and the level of navigation threat. The effectiveness of digital routing based on multicriteria analysis for simultaneously achieving safety and fuel efficiency is proved. The importance of the ISO 31000:2018 standard for the formation of adaptive risk management systems in maritime transport is emphasized.

The results obtained have significant scientific and applied potential. They can be used in the practice of ship-owning companies, dispatch centers, maritime administrations, as well as in the process of crew training. Priority areas for further research include improving risk forecasting models, harmonizing international standards with the specifics of the Ukrainian fleet, and implementing unified information and analytical decision support systems.

Keywords

Navigational risks, energy-saving, shipping, multi-criteria planning, digital navigation systems, safety management, IMO indices (EEDI, EEXI, CII), artificial intelligence in shipping, risk assessment, adaptive ship management.

3.1 Introduction

Modern shipping is developing rapidly in the face of growing environmental challenges and stringent international regulatory requirements. Reducing greenhouse gas emissions has become a key issue for the shipping industry, leading to the emergence of new approaches to energy-efficient ship management. At the same time, ensuring navigation safety remains a priority, requiring consideration of complex and interrelated risks that arise during navigation in an environment of heightened uncertainty. As a result, there is a need to develop integrated approaches that simultaneously achieve energy efficiency goals and ensure navigation safety.

Global shipping demonstrates a steady increase in the volume of maritime traffic, which accounts for more than 80% of international trade [1].

The expansion of vessel sizes, the complexity of operational processes, and growing efficiency requirements pose new challenges to maritime safety.

Despite the development of shipbuilding and navigation systems, the number of serious accidents remains stable, indicating that existing risk management approaches are not sufficiently effective [2].

Particularly noteworthy is the impact of the human factor, which, according to numerous studies, is responsible for 75% to 96% of maritime accidents.

The review [2] systematizes data on the impact of psychological, organizational and ergonomic factors on shipping safety.

Paper [3] emphasizes the importance of applying human reliability analysis methods to help predict behavioral deviations of personnel in critical situations.

Paper [4] develops a fundamental "Swiss cheese" model that demonstrates how multiple levels of protection can be ineffective under a certain combination of human and organizational errors.

In today's digitalized maritime industry, world scientists propose using artificial intelligence methods to analyze large amounts of data, which allows for earlier detection of threats [5].

Research [6] shows that a safe climate in companies and the size of the fleet play a key role in preventing incidents. The relevance of the study is due to the fact that existing energy efficiency management strategies mostly consider economic and technical factors, while not sufficiently taking into account navigation risks. This can lead to decisions that reduce the efficiency of ship operation in a particular navigation situation. Risk assessment is becoming a key element in optimizing decisions related to route, speed, ship systems and fuel consumption.

The aim of the study is to develop methodological approaches to taking into account navigational risks in the system of energy-efficient ship management to improve the efficiency and safety of maritime transport. The subject of the study is navigation risks and their impact on the parameters of energy efficiency of ship operations. The object is the process of managing the operational characteristics of a vessel in the face of external and internal risks.

The objectives of the study include: analyzing existing risks in shipping, studying methods for their assessment, investigating the relationship between navigation risks and energy efficiency parameters, and developing a decision-making algorithm that takes into account both factors.

The scientific novelty of the work lies in the systematic approach to the integration of navigation risk models with energy management systems, which allows for synergy between safety and efficiency of ship management. The practical significance of the obtained results lies in the possibility of implementing the proposed models in automated decision support systems for shipmasters and dispatch services.

3.2 Theoretical foundations of energy efficient ship management

The current state of maritime transport is determined not only by increasingly stringent environmental requirements, but also by the need to improve the economic

efficiency of fleet operations. Shipping companies are focusing on the rational use of energy resources, reducing fuel costs and complying with international sustainability standards. In particular, according to the policy of the International Maritime Organization (IMO), all ships must comply with a number of regulations, such as the Energy Efficiency Design Index (EEDI) for newly built ships, the Energy Efficiency Existing Ship Index (EEXI) for existing ships, and the Carbon Intensity Indicator (CII), which determines the intensity of carbon emissions during fleet operation [7].

Meeting IMO requirements means that shipowners must implement both technical solutions (hull shape optimization, modernization of propeller and rudder systems, transition to alternative energy sources) and operational measures. Among the latter, smart voyage planning is particularly important, including weather forecasting, speed optimization (e.g. slow steaming), route analysis with regard to navigational complexity, and the implementation of decision support systems (DSS) [8].

However, despite the undoubted benefits of energy-saving practices such as reducing speed or changing trajectory, they cannot be applied without risk analysis. For example, reducing speed in narrow or confined waters reduces the vessel's maneuverability, which can lead to accidents such as collisions, piles, and groundings.

In 2013, the IMO introduced EEDI for new ships, which measures energy efficiency in g CO₂/tons-mile, stimulating technical innovation (lower combustion quality, optimized propulsion systems, improved hulls). Stiffness requirements are expected to be tightened every five years, with a minimum 30% efficiency improvement required by 2025.

In June 2021, the IMO adopted amendments to the EEXI (technical assessment of the changed energy efficiency of ships over 400 GT) and CII (annual monitoring of the CO₂ emissions indicator) - both came into force on 1 November 2022, and their mandatory implementation began on 1 January 2023 [9]. The CII includes a rating of ships from A (best) to E (worst); ships with a D rating for three consecutive years or E for one year must submit corrective measures.

The IMO has set a target of reducing the carbon intensity of shipping by $\geq 40\%$ by 2030 compared to 2008, with a further goal of zero emissions by 2050 [7].

Scientific research emphasizes the need to combine energy management with navigation risk analysis. For example, risk assessment at the stage of voyage planning (Risk-based Voyage Planning) helps to avoid a conflict between economic feasibility and safety [10].

Digital navigation systems play an important role in this process. In particular, the use of ECDIS electronic charts with hydrographic information quality assessment (CATZOC) allows calculating the permissible dynamic water reserve under the keel, taking into account chart errors, hydrometeorology, ship draft and pitch.

This is especially relevant in complex areas such as canals, port approaches, and river mouths [11].

An additional means of improving safety and energy efficiency is the Trajectory Points methodology. It allows not only to plan a course but also to identify high-risk areas, such as fairway bends, areas of limited depth, and pile-up zones.

An analysis of accidents on the above-mentioned canals in 2015–2021 showed that the vast majority of incidents occurred due to insufficient adaptation of speed regimes to hydrological conditions and the navigation situation. In particular, frequent groundings occurred due to neglect of recommendations on permissible draft based on water level forecasts.

This data confirms that the use of dynamic decision support systems based on multifactorial analysis (weather, depths, vessel restrictions, traffic) can significantly improve both safety and energy efficiency [12].

Digital platforms such as Maersk ECOvoyage, NAPA Voyage Optimization and StormGeo are being actively implemented around the world, providing automatic route adjustment depending on changes in the environment [13]. This allows to reduce fuel consumption by 3–7% depending on the vessel class [8].

According to the updates to the Ship Energy Efficiency Management Plan (SEEMP Part III), each operator must create an operational plan for CII improvement that takes into account both route performance and planned upgrades [7]. The document should also specify risk management mechanisms in accordance with ISO 31000:2018, which emphasizes the importance of assessing the impact of each management decision on safety [14].

Modern software allows to generate dynamic risk maps, taking into account real-time data variables: AIS, VTS data, weather forecasts, water levels, and the movement of other vessels. For example, the use of Big Data and machine learning algorithms in platforms such as Fleet Operations Solutions allows not only to optimize the course but also to predict danger long before it occurs [15].

3.3 Theoretical foundations of navigation risk management

Navigational risk is the probability of an undesirable event occurring during a sea voyage, which may have negative consequences for the crew, vessel, environment or cargo. According to research, navigation risk arises from a number of factors: technical, technological, environmental and human. IMO recommends defining risk as the product of the probability of an event and the severity of its consequences. This allows not only to classify risks but also to assess their priority. The main types of risks

are technical, technological, environmental, human, and the latest ones related to the introduction of artificial intelligence. Each of them has its own nature and specifics, but in the practice of maritime transport, they often operate simultaneously, reinforcing each other. The human factor remains the most common cause of accidents. Crew mistakes, fatigue, and non-compliance with procedures remain relevant even in the face of automation. The introduction of digital solutions is accompanied by new threats, such as AI algorithm failures, cyber attacks, and imperfect interfaces. This is compounded by natural phenomena such as climate change, storms, icing, and shifts in seasonality. Modern shipping is gradually forming an understanding of the systemic nature of risks, which requires not only the identification of hazards but also the development of adaptive models for their analysis. Thus, effective risk management requires a combination of technical expertise, digital monitoring technologies, and the active participation of the crew in creating a safe environment on board [16].

Navigation risks are a set of potential threats that may arise during a sea voyage and affect the safety of the vessel, crew, cargo and the environment. Managing these risks is a prerequisite for ensuring the smooth, efficient and safe operation of ships in modern shipping. The concept of 'navigation risk' covers a complex system of inter-related technical, natural, organizational and human factors that form the potential for an accident to occur.

Scientific research shows that navigation risks should be classified according to various criteria: sources of occurrence, probability of occurrence, severity of consequences and scale of impact. In particular, the systematic approach considers the division into technical, human, environmental, organizational and emerging risks (e.g., those related to digital systems and AI. An important factor is also the consideration of synergistic effects and systemic interaction of elements, which complicates the forecasting of identified risks.

One of the fundamental principles of risk management is the need not only to identify risks, but also to analyze, monitor and respond to them as part of voyage planning. Domestic researchers have shown that traditional methods of transition planning, as set out in the Bridge Procedures Guide, are insufficient in terms of forecasting and taking risks into account. In particular, the current IMO recommendations do not include a separate stage of navigational risk assessment when planning a route. This requires modernizing approaches to risk management through the introduction of engineering analysis, the construction of hazard matrices, and improved way-point planning that takes into account the ship's maneuvering properties in real time.

The results of the statistical data analysis show that the most common risks are grounding, collisions, piles and equipment failure. In each case, there are certain accident-prone sections of the route for which the probability of an incident can be

calculated based on historical data and the physical and geographical characteristics of the navigation area. Expert estimation methods, such as those used by insurance companies, allow modelling the sequence of events, their consequences and economic losses. Engineering methods, on the other hand, rely on quantitative analysis of the frequency of events and are appropriate for operational analysis immediately before a voyage.

The systematization of risks in the form of classifications, which allow choosing appropriate control and response methods, is of particular relevance. The universal classification proposed by DSTU ISO 31000:2018 Risk Management. Principles and guidelines (ISO 31000:2018, IDT), allows for consideration of internal and external risks, as well as their distribution by the level of consequences - from acceptable to catastrophic. According to this standard, risk management should not only prevent losses, but also contribute to the achievement of shipping objectives by ensuring the sustainability of ship operations (Fig. 3.1).

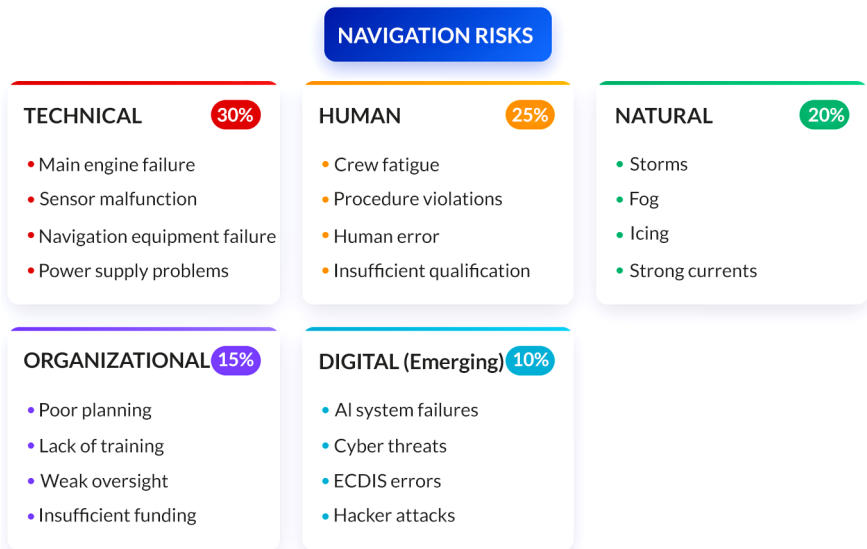


Fig. 3.1 Classification of navigation risks in accordance with ISO 31000:2018
Source: author's own developments based on [17]

Thus, effective navigation risk management requires a systematic approach that combines elements of classification, forecasting, planning, control and correction. The application of such approaches is a key condition for ensuring the safety of

maritime transport and forming a reliable basis for the implementation of energy-efficient ship management in difficult navigational conditions.

3.4 Methods for assessing navigation risks

Navigation risk management is based on a systematic assessment that includes methods for identifying, analyzing, forecasting and controlling hazards during sea crossings. The basis for this approach is the recognition of the limited human and technical resources in a dynamic maritime environment and the need to make decisions under uncertainty. In this context, the role of risk assessment methods as a tool for reducing the likelihood of emergencies and mitigating their consequences is growing.

The most common methods include both qualitative and quantitative approaches. Qualitative methods, such as HAZID, FMEA, SWOT analysis and expert interviews, are focused on identifying potential threats and assessing their impact on safety. They provide a general idea of the level of risk, but their subjectivity limits their accuracy. In contrast, quantitative methods (FTA, ETA, statistical modelling, probabilistic scenarios) are based on the use of accident statistics, technical parameters of ships and sea conditions, which allows for the construction of formalized models with the calculation of the probability and scale of consequences (Table 3.1).

Table 3.1 Comparison of navigation risk assessment methods by type, advantages and limitations

Method	Type	Advantages	Limitations
FMEA	Qualitative	Simple to use, systematic approach	High level of subjectivity
HAZID	Qualitative	Early hazard identification	Does not provide numerical risk values
FTA/ETA	Quantitative	Scenario building, process formalization	Requires large amounts of data and time
FSA	Mixed	Comprehensive analytical approach	High implementation complexity
Risk Matrix	Mixed	Visual control, operational efficiency	Does not account for factor interactions

Qualitative – descriptive analysis without numerical values
 Quantitative – mathematical analysis with numerical results
 Mixed – combination of qualitative and quantitative approaches

Source: author's own development

To make effective management decisions in shipping, it is necessary to implement risk assessment systems that include both quantitative and qualitative approaches. Qualitative methods, such as Formal Safety Assessment (FSA), SWOT analysis, are used to preliminarily identify threats that may arise in an uncertain environment. Quantitative methods, such as Fault Tree Analysis and Event Tree Analysis, allow modelling the probability of events and predicting the consequences. One of the most effective is the FSA method recommended by the International Maritime Organization. It includes five stages: hazard identification, risk assessment, analysis of measures to control them, cost-effectiveness assessment, and conclusion. Additional methods used in maritime practice include HAZID, FMEA and the ALARP principle, which focuses on reducing risk to a level that is reasonably acceptable. The development of digital technologies has helped to adapt these approaches to the real maritime environment. Modern ships use AIS, ARPA, and weather information to build real-time risk assessment models. In particular, risk matrices are effective in the navigation environment, where the level of danger is determined by a combination of the probability of an event and the scale of its consequences. The use of machine learning systems that analyze a large array of historical and current data can improve the accuracy of the assessment and warn the crew of critical deviations in time. All of this contributes to improving the safety of maritime transport and allows for adaptation to environmental changes.

An important role in the risk assessment process is played by building an integrated hazard map that takes into account navigational conditions, vessel characteristics, crew readiness and other factors. Such a map allows to identify the most critical areas of the route at the planning stage of the passage, as well as to adjust the trajectory in accordance with changes in the external environment. Of particular value is the use of trajectory points tied to specific maneuvering parameters of the vessel, which allows for an assessment of the safety margin when navigating in restricted areas.

Engineering assessment methods that use scenario modelling allow to simulate the development of an emergency situation over time, identify key events that may affect its course, and propose preventive measures. Such models are the basis for building digital decision support systems, which are increasingly being implemented in the shipping industry. These systems integrate information from navigational instruments, automatically generate risk levels and suggest the best course of action for the crew.

An important tool remains the method of building risk matrices that combine the probability of an event occurring with the level of its consequences. Such matrices are widely used in maritime practice for rapid situation assessment and

decision-making. Combined with geoinformation technologies, these matrices allow for the construction of dynamic risk maps for the entire ship's route. In addition, modern safety indices (e.g., Navigational Risk Index, Collision Risk Index) provide a quantitative integration of various risk factors into a single model that supports informed decision-making on board.

To summarize, an effective assessment of navigational risks is only possible with the integrated use of both qualitative and quantitative analysis tools, involving digital technologies, mathematical modelling and a systematic approach to managing shipping safety. Further development in this area is aimed at creating adaptive platforms capable of real-time assessment of the situation and offering the safest and most effective scenarios for crew actions.

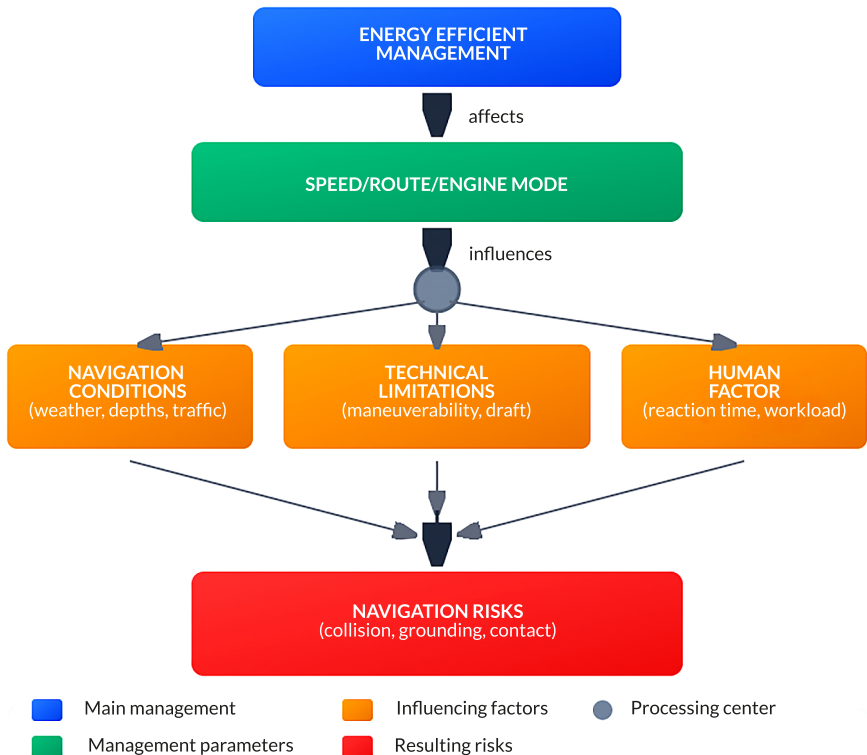
3.5 The relationship between navigational risks and energy efficient ship management

In maritime transport, energy efficient management is closely linked to navigation safety. Reducing a vessel's speed to save fuel can significantly increase risks in the event of unpredictable weather conditions, narrow straits or increased traffic. That is why management decisions must be made with a balance between risk and efficiency in mind (Fig. 3.2). Optimizing a vessel's route involves taking into account a range of parameters, from weather forecasts and traffic to geopolitical factors and environmental restrictions. In practice, this is implemented through the use of multi-criteria analysis, such as AHP or TOPSIS methods, which allow for a reasonable choice between alternatives based on risk, fuel consumption and carbon emissions. Modern digital systems, such as Wärtsilä Voyage or Syro AI, automate route decision-making based on a predictive model that takes into account both economic and safety performance. The use of machine learning algorithms ensures rapid updating of route parameters in response to changes in the situation. This achieves a dynamic balance between energy efficiency and navigational safety. In the future, an important area of research will remain the integration of risk analysis models into the structure of energy management systems and their synchronization with international standards in the field of environmental protection and navigation safety.

Integrating energy efficiency principles into navigation practices requires consideration of navigational risks, as any management decision aimed at reducing fuel consumption may also affect safety levels. This is especially important in difficult hydrometeorological conditions, high traffic intensity, and limited maneuverability in port areas or channels. It is well known that reducing ship speed, as a classic measure

to improve energy efficiency, can negatively affect ship maneuverability, potentially increasing the likelihood of accidents in narrow or shallow areas.

In recent years, research has been actively developing models that combine risk and energy consumption indicators. In particular, an approach is used to construct an optimal route with minimization of the aggregate risk indicator and fuel consumption. This is achieved using multi-criteria models that take into account not only weather conditions and vessel characteristics, but also the probability of critical events along the route. It is advisable to use machine learning elements to predict changes in the navigational environment, which allows the route to be adapted in real time to avoid risky areas.



* Hover over elements for additional information

Fig. 3.2 The relationship between energy efficiency and navigation risks
Source: author's own development

The use of digital vessel traffic services (VTS) and automated navigation systems with real-time risk assessment opens up new horizons for harmonizing safety and energy efficiency. In particular, integrated platforms such as Navi-Planner or Wärtsilä FOS enable dynamic routing that minimizes both fuel consumption and navigational risk (Fig. 3.3). Such solutions are important not only in terms of efficiency, but also for compliance with MARPOL environmental standards and the CII index.

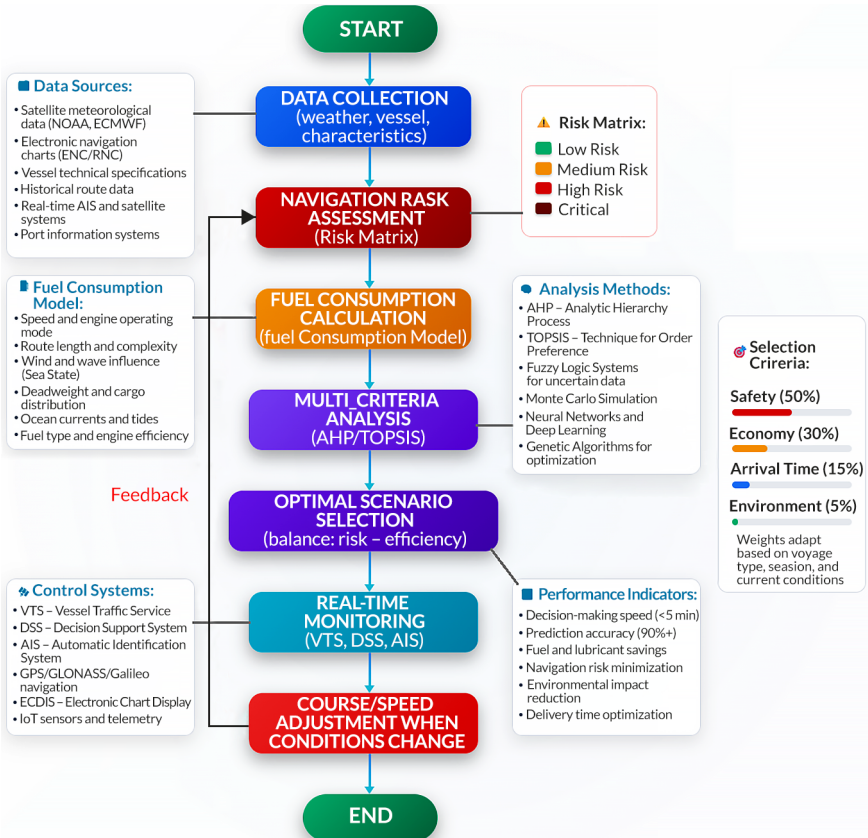


Fig. 3.3 Decision-making algorithm taking account navigation risk and energy efficiency
Source: author's own development

The key to this is the formation of a unified concept in which navigation risks act as a constraint or criterion in the task of minimizing energy consumption. For example,

a route that bypasses a dangerous area with complex bottom topography may be more energy-efficient than a direct but risky route. Therefore, it is important to implement algorithms that give preference to comprehensive assessment rather than isolated optimization of a single indicator.

In conclusion, it should be emphasized that energy-efficient ship management without systematic consideration of navigational risks is a limited and potentially dangerous approach. Only a combination of digital analysis tools, multi-criteria modelling and adaptive management strategies can achieve a sustainable balance between the cost-effectiveness and safety of maritime transport.

3.6 Conclusions

The research showed that effective management of a ship's energy consumption can't be done separately from navigational safety. There's a close link between operational decisions on route, speed, and energy saving, and the level of risks that come up in the marine environment. Global practice shows that neglecting this relationship can lead to an increase in accidents or a decrease in fleet efficiency.

The theoretical foundations of energy-efficient ship management were considered, the main types of navigational risks were classified, and methods for their quantitative and qualitative assessment were analyzed. Particular attention was paid to formalized methods (FSA, ALARP, FMEA), which allow decisions to be justified in conditions of uncertainty. The use of models that combine safety and energy efficiency criteria as a basis for building a multi-criteria decision-making algorithm was proposed. The feasibility of using digital platforms and artificial intelligence to model real-time situations, taking into account risks and fuel consumption, was demonstrated.

The first part demonstrated that the implementation of international requirements for energy efficiency indices (EEDI, EEXI, CII) is accompanied by the introduction of modern digital technologies, route analysis and adaptive management of ship performance parameters. At the same time, traditional speed reduction as a method of energy conservation creates additional risks in complex navigation areas, which necessitates flexible and dynamic control systems.

The second part systematizes approaches to classifying navigation risks by source, nature of origin and scale of impact. Navigation risks cover not only technical and natural factors, but also human factors and digital threats. Effective management of such risks involves not only their identification, but also continuous monitoring and forecasting, as confirmed by examples of accidents in the internal waters of Ukraine and international practice.

The third part is devoted to methods for assessing navigational risks. Both qualitative methods (FMEA, HAZID, SWOT) and quantitative methods (ETA, FTA, statistical modelling) are considered. Particular attention is paid to the construction of integrated hazard maps, risk matrices and digital decision support systems (DSS). It has been established that only the comprehensive use of tools involving data on the vessel, the environment and the human factor allows for a rapid response to changes in the navigational situation.

The fourth part analyses the relationship between navigational risks and energy efficiency. It proves that the isolated application of energy-saving measures without taking safety into account is ineffective. The optimal solution is to use multi-criteria routing models that allow a balance to be struck between safety and economy. The promising nature of digital platforms (Wärtsilä FOS, Navi-Planner) and real-time risk assessment systems for dynamic vessel traffic management has been confirmed.

Thus, the feasibility of implementing a systematic approach to energy-efficient ship management based on an integrated assessment of navigational risks has been substantiated, opening up new opportunities for improving both the safety and cost-effectiveness of maritime transport. Prospects for further research lie in improving mathematical models for risk prediction, developing digital adaptive control systems, harmonizing international standards taking into account the specifics of the Ukrainian fleet, and creating unified information and analytical platforms to support decisions in shipping.

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