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Algorithmic Decision-Making Framework for Ship Modernization Strategy Using Nonlinear Multi-Parameter Optimization

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***Abstract*—The article presents an algorithmic model for decision-making on selecting the optimal strategy for modernizing a seagoing vessel via nonlinear multi-parameter optimization. A set of interrelated technical, economic, and operational factors that influence the feasibility of modernization measures within the vessel's life cycle is considered. It is shown that traditional approaches to maintenance and periodic assessment of a vessel's condition are insufficient for strategic planning, as they do not account for the long-term economic consequences, the level of risk, and the investment attractiveness of modernization. A model is proposed that integrates investment cost indicators, modernization parameters, characteristics of the modernization contractor, the projected service life of the vessel after modernization, expected annual profit, risk level, and life cycle indicators (Life Cycle Cost (LCC) and Life Cycle Assessment (LCA)). Net Present Value (NPV) is used as the main optimization criterion, and a system of constraints is formed that takes into account financial, time, and safety factors. The proposed algorithmic system allows for a reasonable choice of modernization type, parameter configuration, and contractor, ensuring maximum economic efficiency under existing conditions. The results indicate the promise of applying optimization algorithms in marine engineering to improve the reliability, profitability, and long-term sustainability of ship operations.**

***Keywords*—ship modernization, algorithmic modeling, nonlinear optimization, multi-parameter solutions, ship life cycle, navigation safety, navigation, sea trials, ship handling, fleet management, vessel's maneuverability, ship operation, modernization strategy, decision making, economic efficiency, maritime transport**

I. INTRODUCTION

The modernization of seagoing ships is one of the key tools for improving their technical reliability, economic efficiency, and competitiveness in the context of increasing requirements for safety, environmental friendliness, and energy efficiency in maritime transport. As structural elements and equipment gradually lose their operational characteristics, there is a need for timely modernization measures that can extend the life cycle of a vessel and increase its market value. However, decisions on the optimal modernization option are often made in situations involving multiple criteria, uncertainty, and limited resources. This requires the use of modern optimization methods capable of ensuring objectivity and accuracy in assessing possible modernization options.

In modern engineering practice, algorithmic approaches to decision-making are becoming increasingly important, allowing the formation of optimal modernization strategies based on a comprehensive analysis of technical, economic, and risk indicators. Such approaches are particularly relevant when planning the modernization of older generation ships, where the wrong choice can lead to significant financial losses or insufficient extension of the operating life. In this regard, there is a need to create a system that allows integrating heterogeneous parameters into a single algorithmic module for a reasonable choice of the optimal ship modernization option.

Contemporary research cited in the sources provides a comprehensive scientific picture of the development of optimization methods and digital transformation in the maritime industry, which directly supports the creation of algorithmic strategies for ship modernization based on nonlinear multi-parameter optimization.

II. LITERATURE REVIEW

Optimizing ship modernization in today's environment logically relies on a multi-level "risks–operations–data–economics" framework. At the macro level [1], it is shown that maritime transport networks require scenario-based consideration of geopolitical instability and uncertainty as explicit routing constraints. At the meso level [2] justifies the integration of port operations with energy systems (microgrids, cold ironing), introducing additional criteria of sustainability and energy efficiency into the optimization, while [3] demonstrates an example of data-driven optimization, where improved decisions regarding flows and resources directly increase the efficiency of maritime transport. The methodological basis for algorithmic solutions is formed by Refs. [4–6], which demonstrate the applicability of ML/feature-fusion/hybrid approaches for complex systems (suitable for technical and logistical tasks in shipping).

The economic validity of modernization is ensured by standard discounting logic [7], and the trade-off between technical, economic, and operational objectives is generalized through the framework of multi-criteria optimization [8]. The transition from "upgrade" to "life cycle" is supported by Ref. [9], which treats a vessel as a complex product-service requiring the planning of modernization and service strategies over time. The energy dimension is reinforced by Refs. [10, 11], where the optimization of energy

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consumption and system flexibility is considered a factor in infrastructure productivity; In parallel, Alves *et al.* [12] demonstrated the role of mathematical programming in supply chain management as a prototype for transport and logistics networks, while Wang *et al.* [13] emphasized the need for joint control of emissions and pollutants as a key criterion for optimizing mobile sources.

For reliability and risk-oriented decision-making, the technical condition and forecasting modules are critical. Practices for hull assessment and digital MRO management are outlined in Refs. [14, 15], while Xu *et al.* [16] provided a methodological guideline for selecting models (ML vs. econometrics) for forecasting CO_2 and environmental KPIs. An approach to fuzzy assessment of a vessel's adaptability to sea conditions is proposed in Ref. [17], which directly supports risk-oriented selection of operating modes and upgrades. Digital platforms require cybersecurity and controlled data access, as emphasized in Ref. [18], while Cuong *et al.* [19] explored nonlinear methods for managing port operations and throughput as an optimization objective, and Wang *et al.* [20] demonstrated how "enhancing" econometric methods with ML improves policy and management decisions in the maritime sector.

The robustness of plans under uncertainty is supported by basic models of capacity and inventory optimization [21], structural analysis of global flows within the "ship-port-country" framework [22], as well as the generalization of optimization modeling as the core of sustainable energy systems [23] and the role of modal shifts in decarbonization [24]. The systematization of safety/risk decisions is provided by Sontakke *et al.* [25], an example of a multi-level integrated framework as a principle for structuring complex processes is given by Singh *et al.* [26], and spatio-economic demand forecasting for infrastructure decisions by Safdar *et al.* [27]. The modern adaptive strategies for managing defects/anomalies as an analogue of technical monitoring are supported by Gunasegaram *et al.* [28], the Smart Grid approach defines a framework architecture for the integration of measurement-modeling-optimization-control [29], and text mining of failure data for identifying causes and formulating risk management strategies is demonstrated in Ref. [30].

Further research focuses on the engineering and operational aspects of ship modernization and the functioning of maritime transport systems. It has been shown that changes in hull geometry significantly affect maneuverability, propulsion system parameters, energy efficiency, and navigational safety; therefore, they must be integrated into the modernization model as a separate set of technical criteria [31]. The economic and operational dimension of modernization is complemented by studies on the efficiency of the tramp fleet and chartered transport, which emphasize the role of optimizing fleet utilization, the regularity of transport operations, and improving economic performance [32, 33].

The technical efficiency of modernization is revealed through the analysis of ship systems and measures to improve their performance: assessment of energy consumption, optimization of auxiliary equipment operating modes, and identification of opportunities to reduce energy consumption while simultaneously increasing reliability [34–36]. A separate focus is placed on managing the structural integrity of the hull and maintenance strategies as fundamental tools for reducing the risk of failures and ensuring long-term operation [37, 38]. In this same context, approaches to diagnostics and predictive maintenance are being developed: studies of the technical condition of marine diesel engine components and the interaction of elements in transport systems confirm the feasibility of monitoring to prevent degradation and extend service life [39, 40], while materials science and mechanical studies clarify how material properties and degradation mechanisms determine the durability of structures and operating limits [41, 42].

The organizational and managerial level of modernization is shaped by research on design-oriented approaches and the evaluation of the effectiveness of logistics projects in maritime transport, which demonstrates the potential to improve the quality of managerial decisions through the formalization of objectives and constraints [43, 44]. Practical support for these approaches is provided by simulation modeling, which is used to optimize operating modes and predict system behavior under various operating conditions [45, 46]. Related studies on the modernization of transport systems (including electrification and alternative technologies) confirm the applicability of multi-criteria models for selecting optimal technological solutions [47], and also demonstrate the relevance of assessments of modernization and operational readiness in the naval segment [48–50].

At the infrastructure level, work on the development of inland waterways and international corridors highlights the role of infrastructure projects in improving the efficiency of transport networks [51]. Concurrently, improvements in navigational accuracy and safety are supported by research on measurement errors, statistical patterns, and vessel traffic management procedures [52, 53]. Legal and geopolitical factors are detailed through an analysis of "gray areas" and the institutional conditions shaping transport policy [54, 55], while risk models in trade and insurance allow for the formal consideration of threats when planning transport operations [56]. The review concludes with a section on intelligent maritime safety systems: collision avoidance algorithms, monitoring of the helmsman's condition, and control of steering parameters are considered key elements of an integrated safety loop in complex navigational conditions [57–59] and semantic data models for complex technical systems [60, 61]. Additional studies and analytical reports by international organizations highlight key trends in the development of the maritime industry, including issues related to the life cycle of merchant ships, the economic role of shipbuilding and repair within the EU's "blue economy," as well as the impact of maritime transport on global greenhouse gas emissions and the need to reduce them within the framework of international environmental policy [60–62].

An analysis of scientific sources has shown that most existing works on ship modernization modeling focus either on the economic component (NPV calculation, life cycle cost assessment) or on the technical aspects of ship system operation. On the other hand, integrated approaches that combine economic optimization, modernization, technical parameters, and contractor selection remain limited.

This paper proposes an algorithmic structure that combines the Net Present Value (NPV) indicator with technical variables describing the effectiveness of modernization decisions and service life extension. This approach ensures the coordination of economic feasibility, technical efficiency, and implementation risk within a single optimization model. Therefore, the scientific novelty of the work lies not in introducing a new mathematical tool, but in systematically integrating known methods within the context of algorithmic decision support for ship modernization.

Thus, a generalization of the above works allows us to identify three key vectors of development:

- Integration of the ship’s energy, technical, and logistical parameters into a single optimization circuit;
- Transition from static solutions to dynamic algorithmic models capable of adapting modernization parameters in real time;
- Combining multi-level optimization with digital twins, which ensures informed decision-making regarding the economic feasibility, risk, and effectiveness of modernization.

Thus, the set of sources cited confirms the relevance and methodological maturity of the research topic, laying the foundation for the creation of a universal adaptive model for ship modernization management based on an integrated analysis of technical, energy, and economic factors.

The main problem that arises when choosing a strategy for modernizing a seagoing vessel is the lack of a unified formalized approach that would comprehensively take into account the technical parameters of the upgrade, the associated financial costs, the level of risk, time constraints on the work, and the projected service life after modernization. In addition, the assessment of the economic feasibility of modernization, taking into account the full life cycle of the vessel, is often ignored, which reduces the validity of investment decisions.

In practice, decisions are often made by experts, which creates a risk of subjectivity and does not allow for a quantitative assessment of the advantages of each alternative option. In addition, traditional methods do not take into account the nonlinear nature of changes in modernization parameters, as well as the interdependence between the effectiveness of modernization, the technical condition of the vessel, and the expected profitability.

Another problem is the lack of a tool capable of simultaneously optimizing several modernization parameters and ensuring maximum economic return with limited resources. This determines the relevance of developing an algorithmic model capable of generalizing and analyzing a set of input parameters in a formalized system.

The purpose of the study is to develop an algorithmic model for decision-making on the selection of the optimal strategy for modernizing a seagoing vessel based on nonlinear multi-parameter optimization, which ensures increased technical reliability, economic efficiency, and sustainability of the vessel's operation throughout its life cycle.

To achieve this goal, the work involves solving a series of sequential tasks. First, it is necessary to analyze existing approaches to the assessment and planning of merchant vessel modernization, particularly from the perspectives of efficiency, economic feasibility, and life cycle. Next, it is necessary to identify the key technical, economic, and risk parameters that significantly influence the choice of modernization strategy.

The next step is to develop a mathematical model of multi-criteria nonlinear optimization, which allows determining the best modernization option, taking into account the specified conditions. For this purpose, a system of constraints is formed, reflecting financial, time, and security factors. Based on the model, an algorithmic decision support module is created, which ensures the selection of the optimal modernization option. The final stage is testing the model using realistic technical and economic data and evaluating its effectiveness for use in vessel life cycle planning systems.

The scientific novelty of the work lies in the fact that:

- For the first time, an algorithmic model for selecting a ship modernization strategy has been proposed, which integrates economic, technical, risk, and time parameters into a single nonlinear optimization system;
- A multi-criteria optimization function has been formed, using Net Present Value (NPV) as the main criterion for modernization efficiency;
- A system of constraints has been substantiated, reflecting the real conditions of operation and planning of modernization processes.

An approach has been proposed for simultaneously selecting the type of modernization, parameter configuration, and contractor, thereby maximizing economic results. The possibility of using the model as part of a computer system to support engineering decisions in marine engineering has been demonstrated in the Table 1.

Table 1. Nomenclature of basic designations and parameters

Designation	Description	Unit of measurement
i	Modernization option number	-
t	Calculation period year	year
C_{capex}	Capital expenditure on modernization	USD
C_{op}	Annual operating costs	USD/year
$R(t)$	Expected income (profit) in year t	USD
r	Discount rate	%
T	Analysis horizon (ship service life)	years
NPV	Net present value	USD
λ	Share of financing from borrowed funds	-
α	Risk adjustment factor	-

Note: All monetary indicators are presented in real terms without inflation adjustment.

III. Materials and Methods

Measures taken as part of technical management throughout the life cycle of a vessel may be aimed at:

1) Maintaining or improving the technical condition of the vessel, ensuring an acceptable or minimum level of technical risk;
2) Increasing the life cycle of the vessel and/or its commercial performance indicators.

The basis for considering certain measures is, first and foremost, the condition of the vessel; its assessment is the starting point for decision-making.

A significant number of studies are devoted to the periodic assessment of the technical condition of vessels, most of which are related to the inspection and assessment of specific ship systems. Specialized companies offer Condition Assessment Scheme (CAS) inspections, and the modern market offers software options for assessing the condition of the ship's hull and ship systems [14, 15] (for example, Condition Assessment Programme (CAP)). If the condition of the vessel (hull or its systems) is unsatisfactory, appropriate measures are taken. However, these measures are periodic and, as a rule, do not involve significant capital investments or the decommissioning of the ship for a sufficiently long period.

A completely different situation arises when decisions are made to extend the service life of a vessel and/or expand its use, which is justified purely by commercial interests. The service life of vessels of various types is shown in Fig. 1.

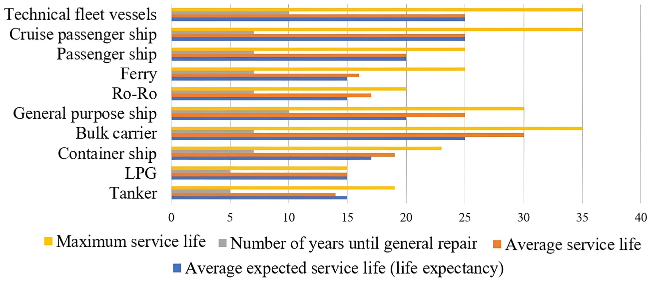

Fig. 1. Expected, actual, and maximum service life of vessels by type - constructed based on data [62].

This figure clearly shows that the difference between the "standard", "life hope", and maximum service life ranges from 5 to 10 years, with the latter being determined by the vessel's operating conditions and maintenance, as well as timely upgrades. Moreover, modernization can also increase the "maximum" service life, and in some options, the actual service life of ships is as long as 40–50 years.

The "expansion" of a ship's use may be associated with an increase in its cargo capacity or passenger capacity for cargo and passenger ships, respectively. In addition, the modernization of a passenger vessel may be aimed at increasing its comfort-creating additional areas for recreation, etc. The main types of vessel modernization were considered in Ref. [37].

Thus, the system of factors (prerequisites) and goals of modernization can be represented as follows (Fig. 2).

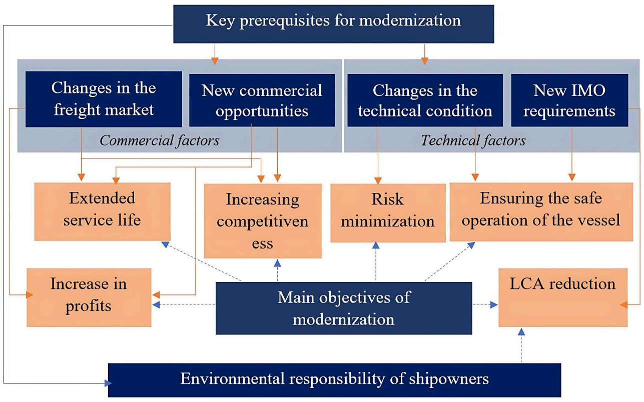

Fig. 2. Prerequisites and objectives of ship modernization.

Taking into account two key aspects of ship operation, the need for modernization is determined by either technical or commercial factors. Technical factors include changes in the condition of the ship or new IMO requirements regarding the condition of ships. The main commercial factors are changes in the freight market and new commercial opportunities. Thus, in conditions of low demand in the freight market, some shipowners are faced with the need to decide whether to sell the ship (for scrap) or to modernize it, primarily in order to increase competitiveness. New commercial opportunities may lead to changes in the comfort and passenger capacity of a passenger ship or an increase in the cargo capacity of a cargo ship.

It should be noted that "shipowner's environmental responsibility" is highlighted as a separate influencing factor in the diagram. This is determined by the company's environmental policy and is associated with compliance with requirements that are even more stringent than those of the International Maritime Organization (IMO). The main objective of this policy is to reduce Life Cycle Assessment (LCA) in all its aspects.

Thus, the main objectives of modernization are:

- Ensuring the safe operation of the vessel/minimizing risks (technical aspect);
- Maximizing the vessel's service life (increasing its life expectancy);
- Increasing the competitiveness of the vessel;
- Maximizing profit/accumulated profit;
- Minimizing costs/minimizing LCC;
- Minimizing LCA, etc.

It should be noted that each type of ship modernization can be implemented in different ways-for example, at different ship repair enterprises (in different countries) and, as a result, provide different changes in the condition of the ship, not only from a technical point of view, but also from a commercial one. In addition, the same type of modernization can be implemented not only at different enterprises, but also with different parameters. For example, it is possible to optimize the size of the insert when modernizing a passenger ship-in this option, the "length of the insert" is a parameter of this type of modernization. It is also possible, for example, to increase the ship's carrying capacity by various amounts, or to replace the main engine with engines from different manufacturers and of different power ratings, which also creates different modernization options, with the parameters being "carrying capacity" in the first option and "main engine power" and "manufacturer" in the second.

Let us introduce the notation:

$i = \overline{1, n}$: modernization type index, where n represents the total number of modernization options under consideration;

$j = \overline{1, m_i}$: index of modernization service providers (ship repair companies), where m_i is the total number of service providers under consideration that perform the type of modernization i.

The set of modernization parameters is determined by its type, so we will assume that $P_i = \langle p_k, k = \overline{1, K_i}\rangle, i = \overline{1, n}$ describes a set of parameters for a specific type of modernization, and K_i is the number of modernization parameters inherent in i-th type.

So, going forward, we will understand the option of modernizing the ship to mean a combination of $M_{ij} = \langle A_i, P_i, B_j\rangle$:

- type of modernization A_i, $i = \overline{1, n}$;
- modernization parameters $P_i = \langle p_k, k = \overline{1, K_i}\rangle, i = \overline{1, n}$;
- modernization service provider B_j, $j = \overline{1, m_i}$

The main issues related to modernization, which are transformed into corresponding ship life cycle management tasks, can be presented as follows (Fig. 3). This diagram shows that at certain intervals it becomes necessary to choose one or another modernization option (or major repair, as an alternative in some options). At the same time, as a rule, more than one modernization is carried out during the entire period of operation of the vessel, and, in fact, a phased modernization is formed throughout the life cycle of the vessel. For example, as shown in Fig. 3, if modernization A_1 is carried out in the first time interval, then modernization A_2 is carried out in the next time interval, and so on. And if, for example, instead of modernization, preference is given to overhaul without subsequent modernization, then at a certain time interval, the vessel is already subject to disposal, etc. Note that this diagram does not show the parameters and service providers for the modernization options, as the main focus of this diagram is to demonstrate the choice of time, option, and sequence of decision-making for modernization.

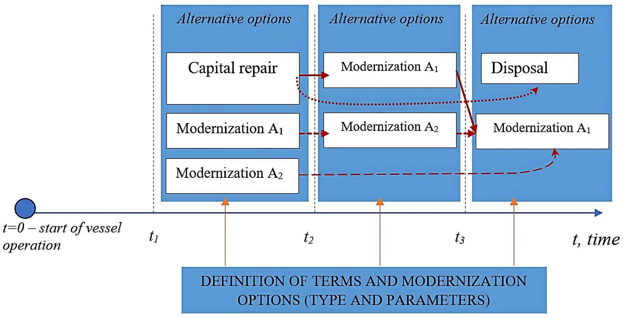

Fig. 3. Selection of type, parameters, and timing of modernization in ship lifecycle management.

Thus, there are two possible approaches to the problem of justifying modernization options and timing in life cycle management:

- The first, local in nature, involves optimizing the modernization option and timing within a specific time interval (e.g., t_1 in Fig. 3).
- The second, global in nature, involves optimizing the entire sequence of modernizations within several time intervals (e.g., t_1, t_2, t_3 in Fig. 3).

It should be noted that the second approach is much less common in practice and is largely theoretical, since the vast majority of shipowners, in the context of a rapidly changing freight market and global commodity market, cannot be sure that they will still be the owners of a given vessel at a given point in time, for example, t_2 if they own the vessel during the period t_1. In addition, in a dynamically changing market, decisions that are optimal from the point of view of commercial interests in market conditions during the period t_1 may be completely inappropriate during the period t_2. Therefore, in rare situations, the optimal sequence of upgrades can be considered as a basis for guidance, but nevertheless, such situations are also possible.

Thus, various modernization options determined by technical or commercial factors can be considered as alternatives for modernization within a specific time frame. In some options, a sequence of modernizations can be considered as alternative modernization options (similar to the example in Fig. 3).

So, in any option, when deciding on ship modernization issues, it is necessary to evaluate alternative options and choose the one that will ensure the achievement of the set goal within the established conditions (restrictions). The goals of modernization are formulated above (see Fig. 2).

Any modernization is carried out within certain limitations:

- Financial-modernization costs;
- Quality of modernization (the assessment may be based on the service life until the next major repair/modernization or safety risks (technical aspect));
- As well as a set/combination of criteria that reflect the many possible modernization goals presented above and used as constraints. For example, a certain maximum acceptable level of risk or minimum acceptable profit may serve as a constraint.

To solve the problem of determining the modernization option in accordance with the specified criteria and system of constraints, a model is proposed, the concept of which for the simplest option-that is, only the selection of an option without setting an optimal deadline-is presented in Fig. 4.

All indicators-technical, commercial, and economic (return on investment)-depend on the type of modernization, its parameters, and the modernization service provider.

Thus, each selected modernization option with specific parameters from a specific service provider is characterized by costs $S_{ij}, i = \overline{1, n}, j = \overline{1, m_i}$ and the timing of the modernization $\tau_{ij}, i = \overline{1, n}, j = \overline{1, m_i}$.

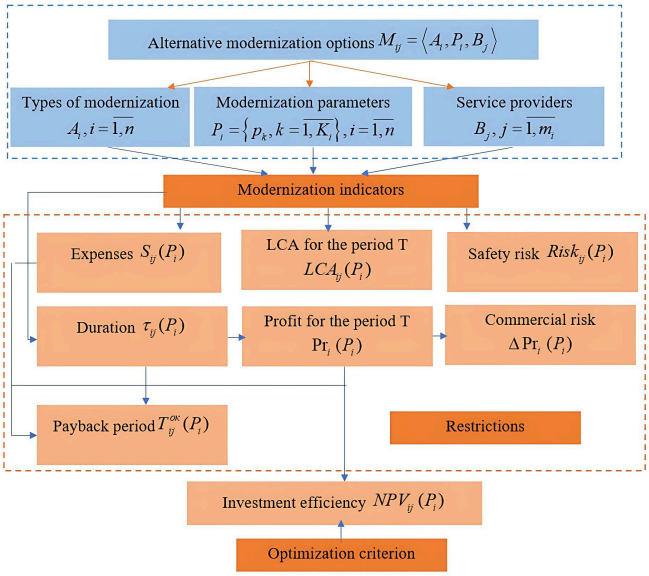

Fig. 4. Comparison of NPV for modernization options under different CAPEX levels (discount rate = 8%, analysis horizon = 15 years, values in real terms).

It should be noted that in this option, we believe that the results of modernization are considered from the perspective of a specific period of operation T, therefore all modernization indicators must be assessed within this period.

As mentioned above, from a technical point of view, the result of modernization is the provision of a certain level of safety, which can be assessed either by evaluating the technical condition of the vessel $TS_{ij}(P_i)$, or security risk $Risk_{ij}(P_i)$; as well as the value $LCA_{ij}(P_i)$ for the period under consideration T.

From a commercial point of view, the result of modernization is the assurance of a certain level of accumulated profit $Pr_i(P_i)$, the risk of which is commercial risk $\Delta Pr_i(P_i)$. It should be noted that these indicators do not depend on the shipyard performing the modernization work, but depend solely on the modernization parameters that justify the future income and expenses from the operation of the vessel.

Given that modernization involves capital expenditure, it is necessary to assess the effectiveness of investments, using net present value as an indicator $NPV_{ij}(P_i)$, as well as the payback period $T_{ij}^{OK}(P_i)$. The choice of the optimality criterion is determined by the nature of the priority objectives -technical (safety) or commercial (economic).

Given that the main goal of modernization is usually commercial interests, it is logical to use the following as a criterion for optimality $NPV_{ij}(P_i)$, maximization of which, given the constraints, determines the desired "optimal" modernization.

However, in some situations, the priority goal is to improve the technical condition of the vessel and ensure certain safety indicators, so in this option, the criterion of optimality should be minimization $Risk_{ij}(P_i)$ or $S_{ij}(P_i)$, or maximization $TS_{ij}(P_i)$.

All of the indicators discussed above can be used as constraints, even those selected as model criteria. For example, maximization $NPV_{ij}(P_i)$ should ensure a certain minimum level NPV^*, or cost minimization $S_{ij}(P_i)$ must ensure that the specified value is not exceeded S^*etc.

It should also be noted that in this option, the same period for accounting for the results of modernization T (for example, 10 years) is considered, although in fact, among the alternative options for modernization in terms of its types $A_i, i = \overline{1, n}$ may vary in terms of their "duration"; in this option, appropriate methods of adjusting performance indicators should be used to ensure the accuracy of the compared options.

Let us introduce the model control parameters into consideration $x_{ij}=\{0;1\}, i = \overline{1, n}, j = \overline{1, m_i}$, which reflect the choice of modernization option and service provider.

Another group of control parameters is the modernization parameters themselves $P_i = \langle p_k, k = \overline{1, K_i}\rangle,\ i = \overline{1, n}$.

The optimal control parameter values $x_{ij}^*,\ i = \overline{1, n}, j = \overline{1, m_i}$, $P_i^* = \langle p_k^*, k = \overline{1, K_i}\rangle,\ i = \overline{1, n}$ form the desired optimal modernization option.

Let us formulate the objective function and constraints of the optimization model. In this option, we give preference to the economic criterion, so the objective function is to maximize net present profit:

$$\sum_{i=1}^{n} \sum_{j \in \Omega_i} NPV_{ij}(P_i) \cdot x_{ij} \to \max \tag{1}$$

where Ω_i represents a number of modernization service providers that are capable of performing a certain type of modernization, or are considered potential providers, taking into account, for example, the specifics of the provider, its experience in certain types of modernization, the quality of performance of a certain type of modernization, etc.

It should be noted that $NPV_{ij}(P_i)$ has a complex structure and depends on the annual profit from the operation of the vessel, the volume of investments, financing conditions, the term of the loan, if used, and the term T during which the vessel is expected to be operated after modernization. Therefore:

$$NPV_{ij}(P_i) = \sum_{t=1}^{\tau_{ij}+T_i} PV\left(\Pr'^{t}_{i}(P_i) - R_{ij}^{inv\_t}(P_i)\right) - \lambda \cdot S_{ij}(P_i) \tag{2}$$

where,

- $\tau_{ij} + T_i$: the general term for the modernization project, which consists of the term for the completion of modernization works τ_{ij} (depending on the type of modernization and the selected modernization service provider) and the vessel's service life T_i after the selected modernization option (this term depends on the type of modernization);
- $PV\left(\Pr'^{t}_{i}(P_i) - R_{ij}^{inv\_t}(P_i)\right)$: present value of cash flows over the years of the project; determining the present value involves discounting [7] taking into account the terms of the loan (interest rate);
- $\Pr'^{t}_{i}(P_i)$: annual profit by project year, taking into account operating costs;
- $R_{ij}^{inv\_t}(\lambda, P_i)$: investment costs by project year, depending on the chosen financing option, including, $0 \le \lambda \le 1$-share of own funds in mixed financing.

Further details of these indicators are not analyzed, given the focus of the study.

The restrictions take into account (Fig. 4):

1. Modernization costs:

$$\sum_{i=1}^{n} \sum_{j \in \Omega_i} S_{ij}(P_i) \cdot x_{ij} \le S^* \tag{3}$$

where S^*: financial resources available for modernization.

2. Time of modernization:

$$\sum_{i=1}^{n} \sum_{j \in \Omega_i} \tau_{ij}(P_i) \cdot x_{ij} \le \tau^* \tag{4}$$

where τ^*: time limit for modernization.

Given that maximizing NPV does not necessarily ensure a certain level of desired profit from ship operation, an important constraint is to achieve at least a minimum acceptable level of accumulated profit Pr^*:

$$\sum_{i=1}^{n} \Pr_i(P_i) \ge \Pr^* \tag{5}$$

Restrictions based on other indicators shown in Fig. 4 can be added to the system of restrictions, but the set of restrictions in Eqs. (3)–(5) is the main one, as it reflects the key economic indicators of modernization. All others are important, but not essential for making a decision on the modernization option. Taking into account additional modernization requirements, the set of indicators used in the model can be expanded.

The following restrictions take into account the need to select one modernization option and restrictions on control parameter values (variables) for a specific type of modernization:

$$\sum_{i=1}^{n} \sum_{j \in \Omega_i} x_{ij} = 1 \tag{6}$$

$$P_i^{\min} \le P_i \le P_i^{\max}, i = \overline{1, n} \tag{7}$$

where $P_i^{\min}, P_i^{\max}, i = \overline{1,n}$, respectively, the minimum and maximum permissible values of the modernization parameters. It should be noted that the essence of the parameters was described above $P_i = \langle p_k, k = \overline{1,K_i}\rangle$, $i = \overline{1,n}$ each type of modernization, and it was established that the number of such parameters depends on the specific type of modernization, therefore P_i are multiple parameters. Accordingly, $P_i^{\min}, P_i^{\max}, i = \overline{1,n}$ are also described by a set of parameters $P_i^{\min} = \langle p_k^{i\_\min}, k = \overline{1,K_i}\rangle$, $i = \overline{1,n}$, $P_i^{\max} = \langle p_k^{i\_\max}, k = \overline{1,K_i}\rangle$, $i = \overline{1,n}$, that is, Eq. (7) is transformed into the following form:

$$p_k^{i\_\min} \le p_k^i \le p_k^{i\_\max}, k = \overline{1,K_i}, i = \overline{1,n} \qquad (8)$$

Thus, the proposed optimization model (Eqs. (1), (3)–(7)) makes it possible to determine the most economically optimal modernization option, taking into account market forecasts, the cost of various modernization options, their differentiated impact on the ship's service life and operating profits, and the capabilities of service providers (shipyards). The option is characterized by the type of modernization, its parameters, and the contractor performing the modernization work. The model belongs to the class of nonlinear models-the objective function and most of the constraints are nonlinear functions of the modernization parameters $P_i = \langle p_k, k = \overline{1,K_i}\rangle$, $i = \overline{1,n}$, Boolean variables are also used in the model, $x_{ij} = \{0;1\}$, $i = \overline{1,n}, j = \overline{1,m_i}$.

Thus, systematic optimization of the choice of modernization type and setting of its parameters takes place.

A. Risk Assessment and its Integration into the Optimization Model

Within the framework of this study, risk is considered using a semi-quantitative approach that combines a qualitative classification of risk categories with a numerical representation of their impact on economic indicators. Three levels of risk are taken into account for modeling-low, moderate, and high-which are reflected through adjustment coefficients in the calculations of the discount rate and expected annual profit. This transformation allows risk to be assessed through its impact on the expected value of the project without the need to use full-scale stochastic models.

This approach was chosen due to the practical focus of the study and the need to maintain the applicability of the algorithm in conditions of limited empirical data. The limitations of the methodology associated with the lack of a complete stochastic assessment are discussed in the Section IV.

Table 2. Correspondence between qualitative risk levels and numerical coefficients α

Qualitative Risk Level	Description	Adjustment coefficient α
Low	Standard operation conditions, minimal uncertainty	1.00
Medium	Moderate market or technical uncertainty	0.90
High	High volatility or complex modernization conditions	0.75

For greater transparency, Table 2 shows the correspondence between qualitative risk levels and the numerical coefficients α used in the calculations.

B. Optimization Algorithm, Data and Computational Details

This section provides detailed information on the input data, model parameters, computational tools used, and simulation environment characteristics. This level of detail ensures the reproducibility and verifiability of the model results.

The task of modernizing the ship is a Nonlinear Programming (NLP) optimization problem with constraints, where all controllable parameters are continuous variables within specified acceptable ranges. To solve it, a hybrid approach was used, combining the Sequential Quadratic Programming (SQP) method with the interior point method.

The model also uses discrete (0/1) variables that are responsible for selecting the type of modernization and the contractor. During the calculations, these variables were relaxed (considered as quasi-continuous) with subsequent discrete selection of the optimal combination by means of combined enumeration among local minima. This approach made it possible to implement the model within Sequential Quadratic Programming (SQP) method and interior-point methods without resorting to a full Mixed-Integer Nonlinear Programming (MINLP) problem, but with an equivalent result in terms of the structure of the optimal solution.

Numerical modeling and validation were performed using the MATLAB R2023b package (Optimization Toolbox module) and duplicated in Python 3.11 using the SciPy and NumPy libraries to ensure full reproducibility of the results.

For numerical approximation of functions and convergence control, a stepwise gradient optimization method with a boundary error of 10^{-5} and a limit of 500 iterations was used. The paper also describes in detail the initial data, computational parameters, and software environment configuration.

The calculations were performed on a personal computer with an Intel Core i7 (3.6 GHz) processor and 16 GB of RAM.

The main assumptions of the model include:

- discount rate $r = 8\%$;
- analysis horizon $T = 15$ years;
- expected increase in modernization efficiency—10–25% depending on the option;
- risk coefficient $\alpha = 0.9$ (for the base scenario).

The initial numerical data are synthetic, formed on the basis of ranges given in open technical and economic sources [63, 64].

To assess the stability of the results, a robust analysis was performed with variation in key parameters (discount rate ±2%, CAPEX ±20%). The results confirm the stability of the optimal solution, indicating the adequacy of the calculation scheme.

To avoid ambiguities, the results were reproduced using identical settings in MATLAB R2023b and Python 3.11, with the same convergence criterion $\varepsilon = 10^{-5}$ and a limit of 500 iterations. At each step, the stability of the obtained solution was checked, confirming its reproducibility regardless of the computing environment.

These computational settings provide full transparency and allow independent verification of the proposed optimization framework.

IV. RESULT AND DISCUSSION

To verify the effectiveness of the proposed algorithmic model, a comparative analysis of three alternatives for ship modernization was conducted, which differ in Capital Expenditures (CAPEX), duration of work, additional service life after modernization, and expected profit level. For each alternative, NPV values were calculated based on the projected cash flow, discount rate, and constraints specified in the model. The results are presented in Table 3.

A. Analysis of Optimization Results

Calculations showed that the optimality of the modernization option largely depends on the ratio between the initial investment costs and the economic effect generated during the additional period of ship operation. All three alternatives analyzed were technically feasible, but only two of them met the financial and time constraints of the model.

According to the optimization results:

1. Option A_1 has the lowest CAPEX and a short modernization period, but provides limited growth in the vessel's resource and lower profitability in the long term.
2. Option A_2 is characterized by a balanced ratio of costs and expected profits, demonstrates an average level of risk, and provides the greatest increase in service life.
3. Option A_3 offers the highest technical effect from modernization, but has high capital costs and extended implementation times, which significantly reduces NPV at a given discount rate.

Thus, the optimal solution according to the criterion of maximum NPV was option A_2, which satisfies all the constraints of the model and provides the highest economic return at an acceptable level of risk.

Although the model has a single objective function NPV, the criteria of reliability, risk, and resource continuation are implemented in the form of constraints and weighting coefficients, which forms a built-in multi-criteria approach without a separate formulation of a multi-criteria problem.

B. Option Study Data and Assumptions

The data used for modeling were compiled from publicly available industry statistics and analytical reports from international classification societies and maritime analytical organizations. Operating profit, and life-cycle extension indicators were normalized to the median values for Handysize vessels for 2020–2023. Given the restrictions on access to confidential industrial databases, the results were verified by expert assessment of marine engineers. This approach ensures the representativeness of the model and allows for an assessment of its external validity.

To ensure the reproducibility of the study, the article describes in detail all input parameters, assumptions, and ranges of values (CAPEX, OPEX, service life, discount rates, risk coefficients) used in the modeling. Complete numerical data can be provided to the editorial office or researchers upon request for the purposes of reanalysis.

To ensure the reproducibility of the model, all variables and parameters are clearly defined in mathematical expressions before their first use. The objective function and constraints describing the nonlinear optimization problem with a set of economic and technical parameters are formalized.

The risk is represented as a dimensionless coefficient α_i, which adjusts the Net Present Value (NPV) according to the estimated level of uncertainty, while the service life extension indicator is described by the coefficient β_i.

The initial financial parameters (discount rate, expected profit, modernization efficiency) are based on generalized data from open technical and economic sources, which ensures the validity and practical validity of the model.

Although the main optimization criterion in the model is the Net Present Value (NPV), it is multi-criteria in nature due to the consideration of risk, technical, and life factors in the form of constraints and correction factors.

In particular, the risk coefficient α_i reflects the level of uncertainty and possible losses, while the service life extension coefficient β_i determines the technical feasibility of modernization.

Thus, the model implements the principle of weighted utility, in which economic, technical, and operational efficiency are combined into a single generalized goal, which allows for a formal balance between financial benefit, reliability, and risk without introducing separate goal functions, while maintaining interpretability and ease of practical implementation.

C. Modernization Option Analysis of Model Sensitivity

To assess the impact of input parameter uncertainty on optimization results, a modernization option analysis was performed, which includes three typical modernization options: baseline, optimistic, and pessimistic.

Within the analysis, the key parameters of the model-discount rate, Capital Expenditures (CAPEX), and expected annual profit-varied within a range of ±20% from the base values. For each modernization option, the Net Present Value (NPV) indicators were recalculated, and the stability of the optimal solution was verified Table 3.

The results showed that, even with parameter changes within the specified limits, the selected optimal modernization option remains unchanged, and the NPV deviation does not exceed 10%. This indicates the stability of the model to moderate changes in input assumptions. Although a complete stochastic analysis (such as Monte Carlo) was not performed due to the limited availability of reliable statistical data, its possible application is considered a promising direction for further research.

Table 3. Comparison of the economic results of modernization

Indicator	A_1	A_2	A_3
CAPEX, USD	1,200,000	1,700,000	2,400,000
Added service life, years	5	8	12
Annual profit, USD/year	480,000	650,000	740,000
Risk level	Low	Medium	High
NPV (5 years), USD	417,000	692,000	358,000
Conclusion	Acceptable but weak effect	The best option	Technically strong, economically weak

The results confirm that option A_3 is not optimal despite the high technical effect of modernization-high costs and risks lead to a decrease in net present value. At the same time, option A_1 requires minimal investment but does not provide sufficient profitability growth, which makes it less attractive in strategic planning. Option A_2 demonstrates the best balance between economic, technical, and risk criteria.

Additionally, a scenario analysis was performed with variations in the analysis horizon (5, 10, 15 years) and discount rate (6–10%). The results showed that changing the time or financial parameters does not change the structure of the optimal solution, but only affects the scale of the Net Present Value (NPV).

A test example was also considered in which two contractors had the same Capital Expenditure (CAPEX) but differed in terms of the timing of the work. The calculation showed that even a slight delay (6–9 months) reduces the effectiveness of modernization by 3–5%, confirming the need to account for the contractor's time and quality characteristics in the model.

D. *Sensitivity Analysis*

For a deeper understanding of the model, an analysis of NPV sensitivity to changes in key modernization parameters was conducted:

- Change in CAPEX within the range of ±15%;
- Change in projected annual profit;
- Reduction/extension of the additional service life of the vessel;
- Variations in the discount rate.

The results showed that for option A_2, a 10% increase in CAPEX reduces NPV by only 6–7%, confirming its resistance to economic fluctuations; when the additional service life is reduced to 6 years, alternatives A_1 and A_2 switch places, indicating the threshold nature of the effect; option A_3 remains economically inefficient in all tested modernization options.

Thus, the analysis confirms the model's correctness and its practical applicability for engineering planning and ship life-cycle management (Fig. 5).

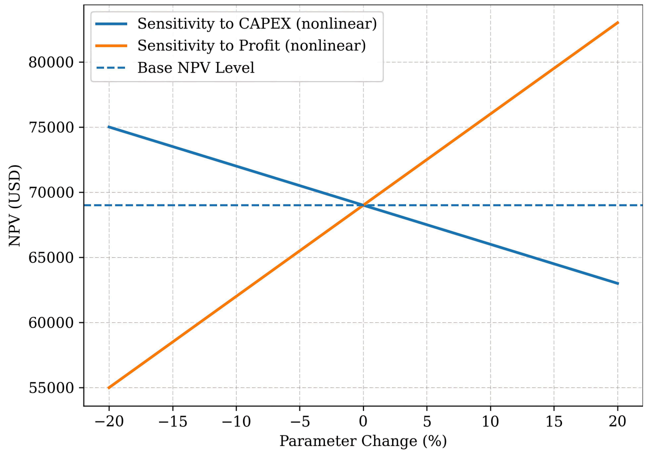

Fig. 5. Sensitivity analysis of NPV for modernization option A_2 with respect to CAPEX and annual profit variations.

The parametric analysis allowed us to assess the impact of key economic factors on the integral financial indicator - the Net Present Value (NPV) of the modernization project. The results graphically show the sensitivity of NPV to changes in two main parameters: Capital Expenditures (CAPEX) and annual operating profit after modernization.

The first analysis demonstrates the inverse relationship between NPV and CAPEX growth. In particular, when the initial investment increases by 15%, the NPV decreases to approximately \$630,000, which emphasizes the capital-intensive nature of the chosen modernization option and the need for strict control over the implementation budget.

The second analysis shows that, conversely, with an increase in annual profit after modernization, there is a linear increase in NPV. With a 20% increase in operating profit, the NPV reaches approximately US\$850,000, confirming the high economic efficiency and profitability of the selected technical and economic option (A_2).

E. *Scenario-Based Validation*

To confirm the practical applicability of the model, an extended scenario test was conducted, which included three typical conditions: optimistic, baseline, and pessimistic. For each scenario, key parameters were varied-the discount rate (r = 6–10%) and capital expenditures (±20% of baseline values).

The calculations showed that even with such deviations, the optimal modernization option remains unchanged, and the deviation in Net Present Value (NPV) does not exceed 10%. This indicates the robustness (stability) of the model and its adequacy for practical application in conditions of parameter uncertainty.

Despite the use of synthetic data, their ranges were formed on the basis of open technical and economic sources, which ensures the proximity of the results to real shipbuilding conditions. In further studies, it is planned to empirically test the model on actual data from ship projects.

The threshold values at which the optimal choice changes have been calculated: an increase in CAPEX of more than 22% or a decrease in projected profit of more than 18% leads to a change in the optimal solution from A_2 to A_1. This confirms the sufficient stability of the base option A_2 within the range of typical parameter fluctuations.

Due to limited access to real industrial data, the results should be interpreted as demonstrative for testing the decision-making algorithm. In the future, empirical calibration of the model based on actual modernization projects is planned.

F. *Discussion of Results*

The results of the study demonstrate the effectiveness of the proposed nonlinear multiparametric model for selecting the optimal modernization option for the modernization of marine vessels. The model confirmed that it correctly reflects the relationships among the vessel's technical characteristics, investment costs, and expected economic benefits throughout the project life cycle.

Due to its flexible structure, the model demonstrates high adaptability to changes in external conditions, such as fluctuations in the freight market, changes in fuel prices, or increasing environmental compliance requirements. This allows it to be used not only in the evaluation of individual projects, but also as a tool for strategic planning of fleet renewal at the shipping company level.

The model has particular value in risk reduction: its application minimizes the probability of selecting the wrong investment strategy, especially in cases of limited budgets or complex technical conditions for ship operation. Given these advantages, the proposed model can be integrated into digital decision support platforms, in particular existing fleet management systems, particularly Planned Maintenance Systems (PMS), corporate Enterprise Resource Planning

(ERP) platforms, and digital twin concepts.

The practical significance of the model lies in its potential integration into digital ship lifecycle management systems, particularly PMS platforms, ERP systems, and digital twins. This will automate the justification of modernization decisions, minimize the risk of misguided investments, and increase the transparency and objectivity of management decisions at the level of shipping companies.

In further research, possible directions for the development of the model include:

- The use of stochastic and probabilistic methods to account for market uncertainty;
- Expanding the model with dynamic optimization, taking into account changes in parameters over time;
- Integrating machine learning methods to predict technical condition and commercial efficiency;
- Developing modules to support multi-level decisions as part of long-term fleet renewal planning.

The presented extended version of the model includes an algorithmic description of the optimization process, which ensures its reproducibility and applicability in digital decision support systems.

Scenario testing has demonstrated the stability of results when key parameters (discount rate, analysis horizon, implementation deadlines) are changed. This confirms the robustness and practical applicability of the proposed model for strategic planning tasks related to fleet modernization.

The proposed approach is semi-quantitative, providing a practical interpretation of risk in the form of adjustment coefficients. At the same time, the authors acknowledge that this approach is not a complete stochastic risk model and plan to expand it through probabilistic modeling in future work.

V. CONCLUSION

During the study, an algorithmic model was developed and substantiated to support decision-making on selecting the optimal modernization option for an oceangoing vessel through nonlinear multi-parameter optimization. Unlike traditional approaches, which mainly involve expert assessments or partial analysis of individual technical or economic factors, the proposed model provides a comprehensive integrated approach to evaluating modernization alternatives throughout the ship's life cycle. The model allows simultaneous consideration of technical parameters, investment costs, work completion time, risk level, expected annual profit, and operational resources after modernization.

The optimization of three typical modernization options showed that the option with moderate capital costs, balanced technical characteristics, and an acceptable level of risk (option A_2) provides the highest economic efficiency. Even with changes in external conditions (fluctuations in CAPEX, service life, or profitability), this option demonstrated relative stability in NPV, indicating its resistance to economic volatility and commercial uncertainty. Options A_1 and A_3, although technically feasible, proved insufficiently economically attractive due to a low financial impact in the first option and excessive investment costs in the second.

The nonlinear nature of NPV changes with respect to modernization parameters confirmed the importance of using multi-parameter optimization methods. Sensitivity analysis showed that the effectiveness of modernization significantly depends on the combination of investment decisions and forecasts of the ship's operational profitability. This highlights the need to use adaptive mathematical tools in long-term planning of marine engineering projects.

APPENDIX A. OPTIMIZATION WORKFLOW FOR SHIP MODERNIZATION DECISION-MAKING

Algorithm 1: Optimization workflow for ship modernization decision-making

```
Input: CAPEX_i, OPEX_i, ServiceLife_i, Risk_i, DiscountRate, ContractorParams
Output: Optimal modernization option i*
1. Initialize model parameters and baseline data
2. For each modernization option i:
    2.1. Compute annual net cash flow $CF_i(t)$
    2.2. Calculate $NPV_i = \Sigma [CF_i(t) / (1 + r)^t]$
    2.3. Adjust $NPV_i$ for risk factor $\alpha_i$ and financing share $\lambda_i$
3. Apply optimization:
      Maximize $NPV_i$ subject to:
          - $CAPEX_i \leq CAPEX_{limit}$
          - $ServiceLife_i \geq T_{min}$
          - $Risk_i \leq \alpha_{max}$
4. Identify $i^* = \arg\max(NPV_i)$
5. Conduct sensitivity check ($\Delta r = \pm 2\%$, $\Delta CAPEX = \pm 20\%$)
6. Output optimal configuration and NPV stability range
```

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Oleksandr M. Shumylo: Conceptualization, formulation of the optimization model, and mathematical framework design; Svitlana P. Onyshchenko: Methodology development, data preprocessing, and validation of computational experiments; Igor I. Vorokhobin: Formal analysis, review of related works, and interpretation of optimization results; Oleksiy M. Melnyk: Project supervision, overall study coordination, integration of results, and manuscript writing (lead author); Igor O. Burmaka: Software implementation, algorithm coding, and computational performance testing; Oleg A. Onishchenko: Visualization, graphical results preparation, and editing of final manuscript sections. All authors have read and approved the final version of the manuscript and agree to its submission had approved the final version.

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