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Towards Efficient Ship Design: A Review of Methods and Attributes for Decision-Making in Ship Selection

Chao Edwin Giovanny Paipa- Sanabria[1, 2,*] George Fernández-Alonso[3], Daniel Gonzales Montoya[4], Jairo Coronado- Hernandez[1]

1 Department of productivity and innovation, Universidad de la Costa, Barranquilla, Colombia. Email: epaipa@cuc.edu.co, jcoronad18@cuc.edu.co
2 Ship Design and Engineering Department, COTECMAR, Cartagena, Colombia. Email: epaipa@cotecmar.com
3 Office of Research, Instituto Tecnológico Metropolitano, Medellín, Colombia. Email: gfa20900@hotmail.com
4 Faculty of Engineering, Instituto Tecnológico Metropolitano, Medellín, Colombia. Email: danielgonzalez@itm.edu.co

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ABSTRACT

With the increasing sophistication of naval systems and the rising imperative for environmentally sustainable solutions, it becomes crucial to understand how multi-criteria decision-making (MCDM) models facilitate informed decision-making to ensure vessel performance and sustainability throughout their life cycle. This research undertakes a systematic literature review of MCDM applications across various stages of the ship life cycle from a systems engineering standpoint. Particular attention is given to the design phase, where MCDM approaches are employed to determine the most appropriate ship configuration, considering factors such as operational capabilities, effectiveness, and performance metrics. A total of 131 studies were examined following the PRISMA methodology, with data sourced from Scopus and the Web of Science. The review concentrated on design methodologies, hierarchical structuring, and the assessment of essential decision-making criteria, including cost, effectiveness, and risk. The results demonstrate that MCDM models not only support the identification of optimal ship configurations but also assist in evaluating their effects on operational efficiency and environmental sustainability. The study underscores the importance of incorporating a range of performance measures, including Measures of Effectiveness (MOE), Measures of Performance (MOPs), Technical Performance Measures (TPMs), and Key Performance Parameters (KPPs), to strengthen decision-making in both design and operational contexts. Finally, a framework is proposed to guide the selection of vessels that are both operationally efficient and environmentally compliant, in line with contemporary regulatory requirements.

1. Introduction

The acquisition of a vessel represents a strategic undertaking that integrates technical, financial, and legal evaluations to ensure both the operational and economic viability of the project. This

* *Corresponding author.*
E-mail address: epaipa@cuc.edu.co

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process involves identifying specific requirements based on the intended operation, selecting according to vessel capabilities and routes, assessing total costs including purchase, maintenance, and operation, adhering to customs and registration regulations, and formalizing financing and procurement. These elements are coordinated within a framework that ensures alignment with commercial and regulatory objectives [45]. Applying systems engineering principles, a vessel is regarded as a complex system comprising multiple interconnected components, each performing a distinct function to enable maritime or riverine navigation and fulfil mission objectives [81].

Viewing the vessel as an integrated system of interrelated subsystems highlights the critical importance of life cycle planning to maintain uninterrupted operations. Implementing evaluation techniques during the early stages of the vessel life cycle ensures optimal performance, resource efficiency, and an extended service life, while fulfilling design objectives [44]. It has been noted that a significant proportion of a system's total cost is determined in the initial phases of development [64], emphasizing the strategic importance of early decision-making during the planning and conceptual design stages, as these choices have long-term implications for cost, risk, and system performance. In this context, MCDM models assume a key role by providing a structured and transparent framework to assess design alternatives across technical, operational, economic, and environmental dimensions. This study examines the utilization of MCDM models within the naval sector, focusing on vessel life cycle phases and analyzing hierarchical decomposition (systems, subsystems, components, and consumables), MOE, MOP, TPM, and the MCDM methods employed for selection. The findings are expected to assist a broad spectrum of stakeholders within the naval industry.

Project managers, ship-owners, shipping companies, end users, and shipyards can leverage the results to develop and select more effective decision-making models that support the identification of the most suitable ship design, ensuring compliance with technical, economic, operational, and environmental requirements. Additionally, the study contributes to a deeper understanding of key decision-making concepts and attributes, fostering a comprehensive project perspective when evaluating vessel design alternatives. The primary objective of this research is to establish a structured framework of technical, environmental, social, and regulatory attributes and criteria for developing or selecting an MCDM model. To accomplish this, the study poses the following research questions:

- RQ1: According to the ESWBS applied to vessels, at what hierarchical decomposition levels have MCDM techniques been investigated?
- RQ2: At which stages of the vessel life cycle have studies on multi-criteria decision-making focused?
- RQ3: What attributes or criteria are commonly considered in the multi-criteria decision-making models applied to the selection, design, and operation of vessels?
- RQ4: What MCDM techniques have been used in the selection, design, optimization, and operation of vessels as Systems of Interest (SOI)?

The subsequent sections of this study commence with a comprehensive literature review, focusing on the vessel life cycle, systems engineering principles, and the application of MCDM models within the theoretical framework. Following this, the methodology adopted for the literature review is presented in detail. The results are then reported and critically discussed, addressing the research questions and outlining a framework for vessel selection based on the prevailing general attributes. The study concludes with an evaluation of its limitations, propositions for future research, and final conclusions, emphasizing the principal insights and contributions derived from the research.

2. Literature Review

The complexity inherent in vessel development necessitates a comprehensive analysis of their systems, operational performance, and capabilities, with the aim of satisfying the diverse requirements of stakeholders. Based on the diffusion of innovations theory, these requirements can be categorised into four domains: perceived usefulness, effort expectancy, social influence, and facilitating conditions. This framework indicates that vessel design must integrate considerations of economic, logistical, ergonomic, quality, health, safety, image, and, more recently, social and environmental sustainability factors [79], while simultaneously addressing the specific functional objectives of the vessel [79]. Such a configuration of features can be conceptualised as an interconnected and functional system, where design and development constitute a highly intricate process. For vessels, this necessitates a holistic approach encompassing component configuration, objective formulation, and structured decision-making throughout the design stages.

A review of the literature on vessel design highlights several surveys focusing on system configuration that seek to incorporate emerging decision-making dimensions to align human activities with regulatory standards, thereby enhancing viability and sustainability. Studies exploring related applications include the use of MCDM techniques for sustainability in energy systems development [7], bibliometric analyses of alternative fuel selection in maritime operations [65], investigation of alternative selection in ballast water management systems [46], evaluation of vessel recharging station placement considering geographical and climatic factors [19], assessment of dredging operations for environmental compliance [57], and the design of hydrogen storage containers [91]. Further approaches aligned with the objectives of this study include the application of the weight-of-evidence (WoE) method to assess environmental and health risks [49], the use of MCDM techniques in sustainable supply chain configuration and supplier selection [35; 39], and reviews of MCDM applications in planning and selecting strategies for deep-sea mining [53]. Finally, three literature reviews directly addressing vessel selection are noteworthy. One provides a technical definition of vessels crucial for identifying effectiveness parameters [13], another examines the hierarchy of effectiveness and classifies operational and physical performance indicators [34], and a third reviews methods employed in vessel acquisition with a focus on emerging sustainability dimensions [8]. The subsequent section presents the findings from these literature reviews, detailing decision-making approaches across various forms of vessel acquisition.

2.1 Technical Definition of a Vessel

The concept of a vessel is defined based on functional recognition and the effective accomplishment of missions [13]. This approach applies the principles of SE and utilises the V-model to offer a comprehensive and detailed representation of a vessel's characteristics across all phases of its life cycle.

The model illustrated in Figure 1 adopts a systematic methodology, encompassing all stages from defining project objectives to identifying technical solutions, while considering the complexities of development, operation, and disposal [16]. During the initial phases (pre-concept and development), the technology is characterised by its technical features and capabilities, whereas in subsequent phases (production and decommissioning), attention shifts to technological scaling and operational deployment. Throughout this process, alignment with the mission objectives of the developed artefact must be maintained [21]. To support this alignment, a hierarchical metric system is employed to validate the capabilities of the system from the overarching concept down to its most specific elements, structured into five levels [13; 34; 36; 71]:

- Measures of Effectiveness (MOEs): Evaluate the extent to which the primary mission is accomplished, considering the operational environment.

- Measures of Performance (MOPs): Describe in qualitative terms the physical and functional characteristics of the system that contribute to mission success, providing greater detail than MOEs.
- Technical Performance Measures (TPMs): Quantify the degree to which MOP-defined objectives are achieved, using physical dimensions or performance values. Each MOP may be associated with multiple TPMs.
- Key Performance Parameters (KPPs): Specify the precise quantitative targets that TPMs must meet to satisfy mission requirements.
- Dimensional Parameters (DPs): Represent measurable physical attributes and properties of the evaluated artifacts.

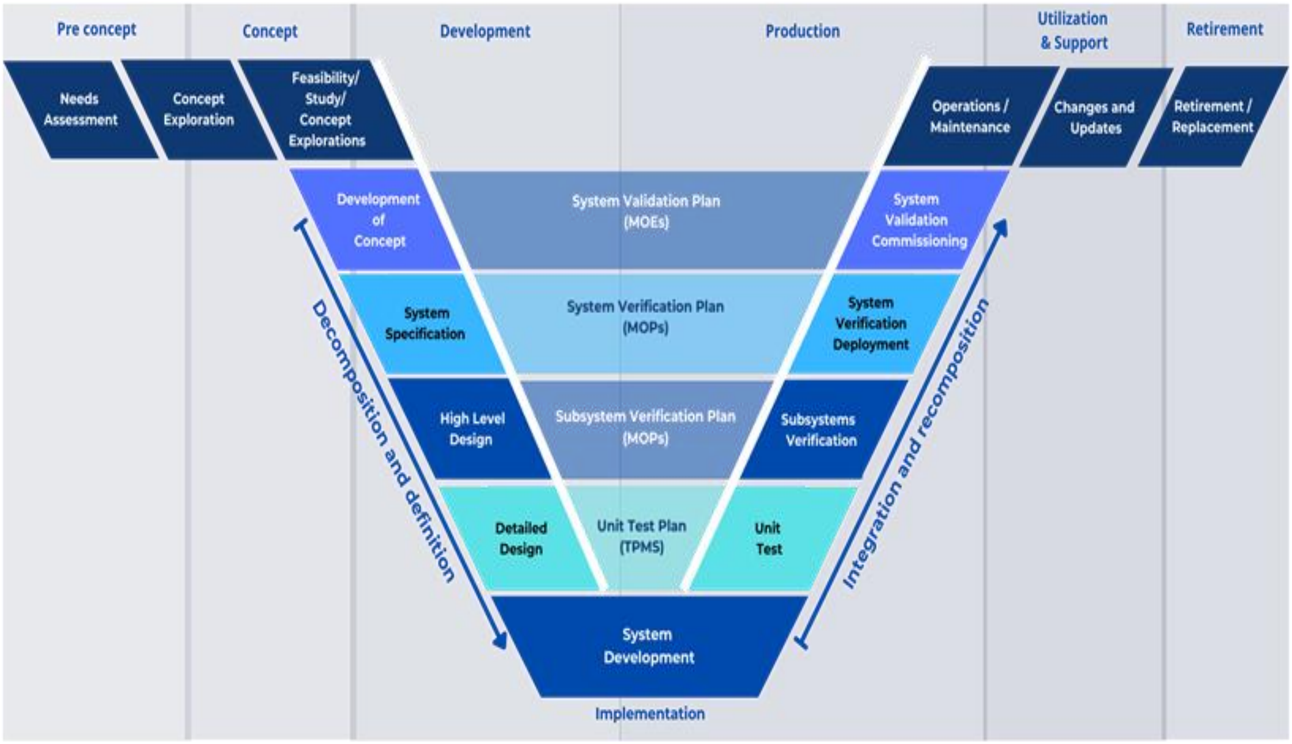

Fig.1: V-Model of Systems Engineering (Own Elaboration Based on[13])

The Royal Spanish Academy (RAE) [25] offers a general MOE for vessels as vehicles capable of navigating bodies of water with autonomous propulsion; however, this MOE may vary depending on mission type (e.g., tourism, defence, healthcare, transportation). The definition of MOPs, TPMs, and KPPs requires decomposition of the system into subsystems [36]. In naval engineering, ship decomposition is typically carried out following work breakdown schemes widely recognized in the military domain, among which the Expanded Ship Work Breakdown Structure (ESWBS) used by the United States Navy stands out. This framework provides a standardized hierarchical structure for systematically and functionally organizing the elements of a ship throughout its entire life cycle [100].

The ESWBS facilitates life cycle assessments of variables such as cost, weight, specifications, and functionality by classifying technologies into nine primary functional groups (000 to 800) [100; 74]. The technological breakdown also establishes a compositional system hierarchy:

- Level 1 – System of Interest (SOI): The primary analytical unit, decomposed into functional groups that fulfil the MOEs.
- Level 2 – Systems: Major functional groups within the SOI.
- Level 3 – Subsystems: Less complex systems performing specific functions for the broader system.
- Level 4 – Components: Artefacts comprising multiple parts whose operation depends on their

configuration.
- Level 5 – Parts, Units, and Consumables: Single-material units that are either consumable or replaceable to achieve component objectives.

According to NATO [1], vessels are regarded as systems of systems enabling a crew or cargo to navigate bodies of water with autonomous propulsion. Once performance metrics are established, it is possible to evaluate artefacts down to Level 5 of the technological hierarchy. For the purpose of this study, the vessel is considered as the SOI, with its MOPs and TPMs presented in Table 1.

Table 1
MOPs and TPMs of a Vessel (Own Elaboration Based on [13])

Performance Measures (MOPs)	Technical Performance Measures (TPMs)
Buoyancy	Base Buoyancy: Baseline Draft, Required Draft During Operation
	Reserve Buoyancy: Changes in Buoyancy Due to Damage, Wear, or Modifications
	Load Distribution: Operational Buoyancy Under Hydrodynamic Conditions and Submersion
Stability	Intact Stability: Resistance to Inclination Under Normal Conditions
	Damage Stability: Resistance to Inclination in the Presence of Damage
Structural Strength	Global Structural Strength: Structural Resistance to Loads from Operational Stress and Climatic Degradation
	Local Structural Strength: Resistance under Specific Conditions
Power Generation	Propulsion Power Generation: Power Required to Move the Vessel at Sustained and Maximum Speed
	Equipment Power Generation: Electrical Power Generation for Vessel Subsystem Operation
	Emergency Power Generation: Power Generation under Degraded or Emergency Conditions
Control	Propulsion: Ability to Change the Vessel's Speed
	Steering: Ease of Handling and Responsiveness in Vessel Maneuvering
Internal Communication	Internal Communication: Information Systems for Controlling and Directing Internal Operations
Navigation	Detection: Ability to Detect Environmental Changes and Information from Nearby Vessels
	Route Planning: Route Establishment Based on Environmental Conditions
Command and Control	Situation Assessment: Interpretation of Information Received from the Operational Environment
	Support: External Monitoring and Feedback on Operations
External Communication	External Communication: Managing and Maintaining Effective Communication with External Vehicles and Buildings

2.2 Lifecycle and Decision-Making

The NATO model highlights that each phase transition necessitates decisions grounded in project viability, risk, and effectiveness [1]. To organise and standardise this decision-making, the Aerospace Studies Office [71] and the U.S. Air Force [83] developed the Analysis of Alternatives (AoA) methodology, based on SE principles [36]. AoA evaluates three principal dimensions:
- Effectiveness: Ensures that technological development is aligned with hierarchical metrics (MOEs, MOPs, TPMs, KPPs, DPs), guiding objective setting and technical solutions across ESWBS levels.
- Cost: Assesses financial feasibility across the life cycle, including acquisition, investment, returns, operational and support costs, personnel wages, and other economic factors.
- Risk: Examines the likelihood of challenges in planning and execution across technical, programmatic, economic, and operational domains.

Each dimension employs specific evaluation methods and data types that must be optimised to enhance technology integration within the SOI [51]. The inherent complexity of this process complicates the establishment of complete requirements in early phases, rendering the design process iterative, uncertain, and experimental [4; 5].

In the configuration of technology, the application of life cycle analysis (LCA) is crucial for thoroughly evaluating the resources required throughout the transformation, operational, and disposal stages across the supply and value chains [30]. This ensures that both the vessel's intended purpose and its economic feasibility are addressed [3; 24; 47]. Despite advances in standardization, the implementation of LCA remains challenging due to difficulties in precisely defining technological development and the absence of a universally applicable methodological framework across disciplines and product types [36; 89]. Several studies propose life cycle models typically consisting of five phases: concept, development, production, utilization, and disposal [89]. For military vessels, NATO [1] provides a more detailed seven-phase model, as illustrated in Figure 2.

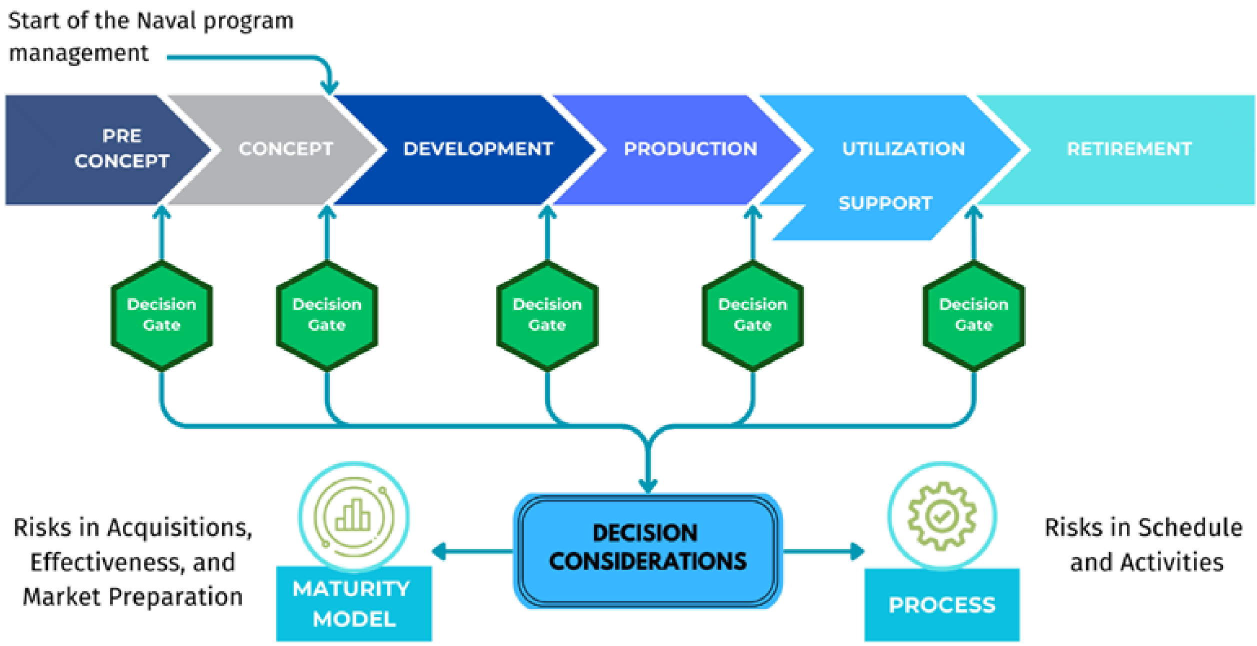

Fig.2: Lifecycle Model (Own Elaboration Based on NATO [68])

Within the AoA framework, MCDM methods serve to balance these dimensions by maximising user satisfaction, consistent with principles derived from innovation diffusion theory [8; 40; 41; 82]. These methods facilitate the identification, characterization, ranking, scoring, and analysis of alternatives, uncovering causal and logical relationships among criteria [49]. Their effectiveness can be further improved through the use of fuzzy logic (for handling imprecise data), rough sets (for approximating interdependencies), and grey systems (for managing incomplete data) [39]. MCDM methods are generally classified into two main categories (as evidenced in Figure 3):

- Multi-Objective Decision Making (MODM): Typically employs mathematical programming or metaheuristic algorithms, suitable for problems with continuous data.
- Multi-Attribute Decision Making (MADM): Applied to problems involving qualitative or discrete data [12; 29].

Model selection in decision-making is not mutually exclusive, as hybrid approaches combining MODM and MADM have been developed to accommodate diverse attributes, criteria, and variables [50; 61]. Within the naval sector, MCDM applications address a broad spectrum of criteria spanning technological, environmental, social, economic, regulatory, policy, risk, effectiveness, supply, quality, and reputational dimensions [19; 35]. Owing to its military origins, the AoA methodology is seldom applied in civil vessel selection, where simpler analytical tools are typically preferred [8], despite AoA offering a structured and rigorous decision-making framework.

Fig.3: Classification of MCDM Methods (Own Elaboration Based on [22])

3. Methodology

This study utilizes the PRISMA methodology due to its high level of standardization and widespread academic recognition for conducting systematic literature reviews [73]. PRISMA provides a structured protocol that enhances transparency, replicability, and methodological rigor of review studies. The framework includes a comprehensive checklist and flow diagram that guide researchers through the identification, selection, appraisal, and synthesis of literature relevant to a particular research topic [72]. Following PRISMA guidelines, the process begins with a precise definition of research questions and objectives, followed by the formulation of inclusion and exclusion criteria [62]. These criteria ensure that only pertinent and high-quality studies are retained. Subsequently, information sources and search strategies are defined, employing carefully selected keywords and Boolean operators to capture the conceptual breadth of the subject.

The PRISMA procedure comprises four primary stages [72]. The identification stage involves locating all potentially relevant studies through systematic database searches. During the screening stage, titles and abstracts are examined to exclude studies that do not meet the pre-established criteria. The eligibility stage entails full-text evaluation to verify the relevance and methodological adequacy of each study. Finally, the inclusion stage selects studies that satisfy all requirements for incorporation into the analysis. In this research, the PRISMA methodology was applied to two major academic databases: Scopus and Web of Science. Following the initial search and dataset consolidation, a detailed review was conducted, and documents were categorized according to their application sector, hierarchical decomposition level based on the ESWBS, and the vessel life cycle phase addressed. This categorization enabled a systematic synthesis of the selected studies to address the four research questions. Figure 4 presents the complete flow of the PRISMA-based selection process as implemented in this study.

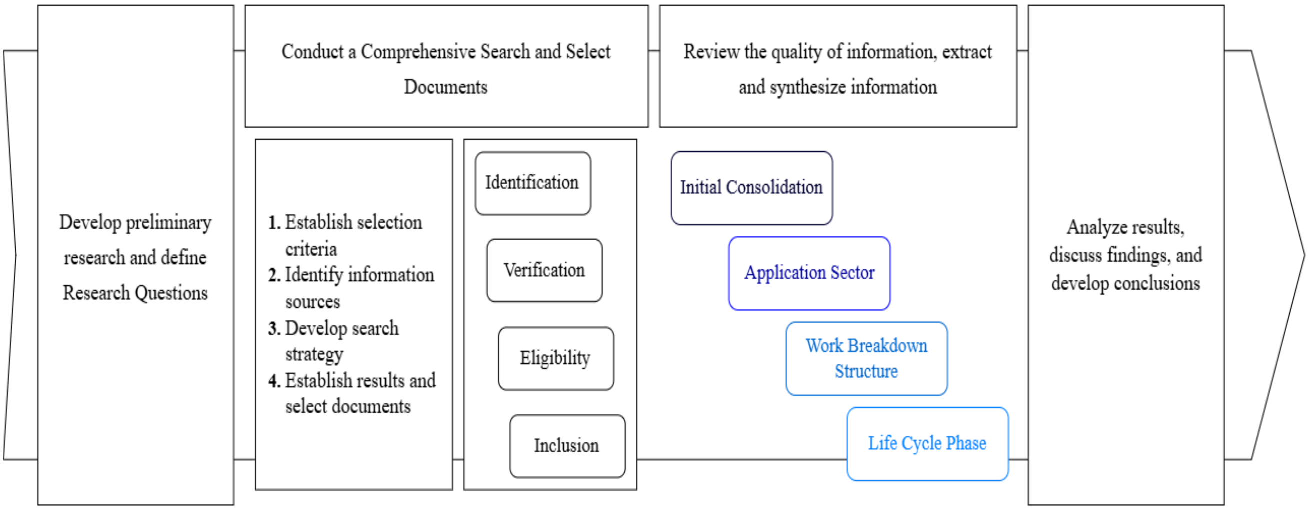

Fig.1: Simplified Steps of the PRISMA Methodology (Own Elaboration Based on[72])

3.1 Selection Criteria

The inclusion of documents adhered to predefined criteria to ensure methodological rigor. As indicated in Table 2, studies were selected based on their relevance to multi-criteria or multi-objective decision-making within vessel design, system selection, or naval components. Only academic, open-access publications in English or Spanish were considered. No temporal restrictions were applied, allowing a broad historical perspective due to the limited number of relevant documents remaining after filtering and deduplication.

Table 2
Selection Criteria

Criterion	Description
Relevance	The selected documents met one of the following criteria: Presented multi-criteria or multi-objective selection techniques for vessel design selection. Addressed the selection of specific systems for vessels using decision-making techniques. Presented decision-making methodologies for selecting naval components.
Document Type	The nature of the documents is strictly academic (Articles, Literature Reviews, Book Chapters, Conference Papers).
Time Coverage	No time restrictions were established in the document search.
Language	Only documents in English and Spanish were included.
Accessibility	Only open-access publications were included, allowing other researchers to verify the results of this study.

3.2 Search Strategy

To identify the key concepts of this study, two keyword groups were established: one pertaining to the naval industry and the other to MCDM. Within each group, terms were combined using the

Boolean operator "OR," while "AND" was applied between groups, enabling the retrieval of documents addressing both areas concurrently. The search equations were applied to specific fields, including title, abstract, and keywords, to maximize relevance, control results, and minimize misinterpretation by the search engine. Table 3 presents the search expressions employed, detailing the strategy designed to capture literature pertinent to the study's objectives.

Table 3
Search Expressions for Document Sample Selection

Group	**Search Expression**
Naval Industry	"Naval industry" OR "Shipbuilding" OR "Shipbuilding Industry" OR "Shipyard" OR "Shipyards" OR "Ships" OR "Ship" OR "Boats" OR "Boat" OR "Vessels" OR "Vessel" OR "Naval Vessels" OR "Fluvial" OR "Maritime" OR "Watercraft" OR "Small craft" OR "Yatch" OR "Sailing" OR "Pushboat" OR "Barge" OR "Ferry" OR "Riverboat" OR "Naval"
MCDM	"Multi-criteria Decision Making" OR "MCDM" OR "Multi-Criteria Decision Analysis" OR "MADM" OR "multi criteria decision making method" OR "AOA" OR "Analysis of Alternatives"

3.3 Selection Process

Following the initial search, filters for accessibility, document type, and language were applied using the database tools. The resulting records from each database were exported in BibTeX format, and duplicates were eliminated using RStudio (version 4.4.2). The cleaned metadata was organised and analysed in a matrix format using Microsoft Excel. Titles, abstracts, and keywords were examined to exclude irrelevant studies, followed by a full-text assessment of the remaining documents. The final set of records was subsequently classified according to their application sector, hierarchical decomposition level, and vessel life cycle phase, in accordance with the research questions. Figure 5 illustrates the outcomes from the identification through the eligibility stage.

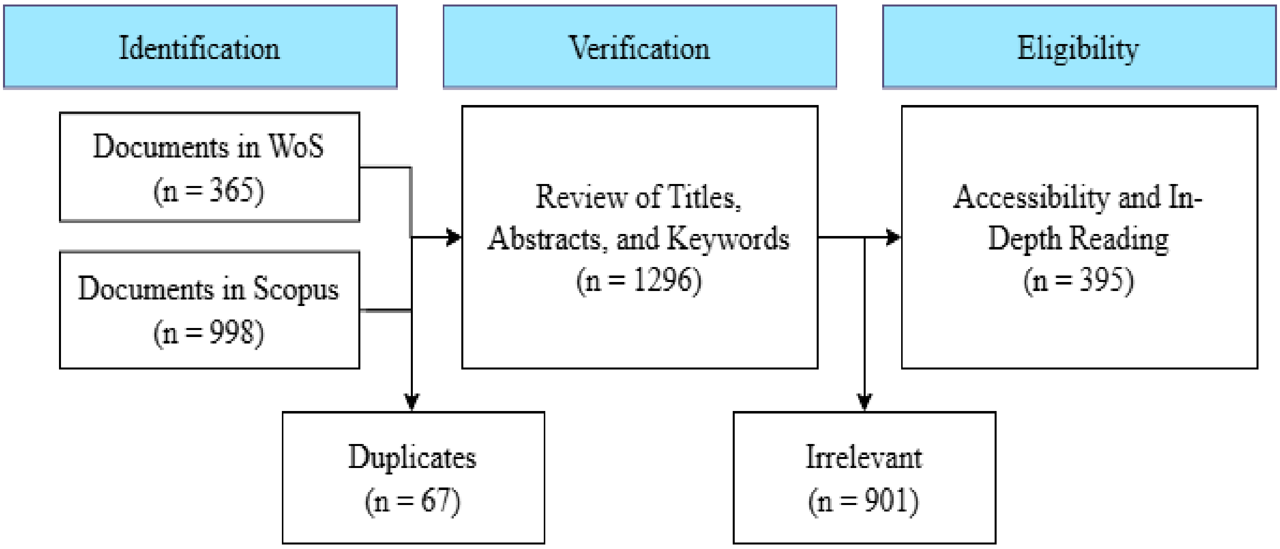

Fig.5: PRISMA Methodology Application Results

4. Results and Discussion

Based on the search results, a total of 395 documents were identified as relevant to the naval industry. These were categorized according to their focus on ports, shipyards, or vessels, revealing that 219 records addressed vessels exclusively. Applying a theoretical framework that incorporated hierarchical levels of analysis, life cycle phases, evaluation dimensions, and MCDM techniques, the sample was refined to 131 general documents and 42 specifically concerning vessels as the SOI. The details of the classification and selection procedure are illustrated in Figure 6.

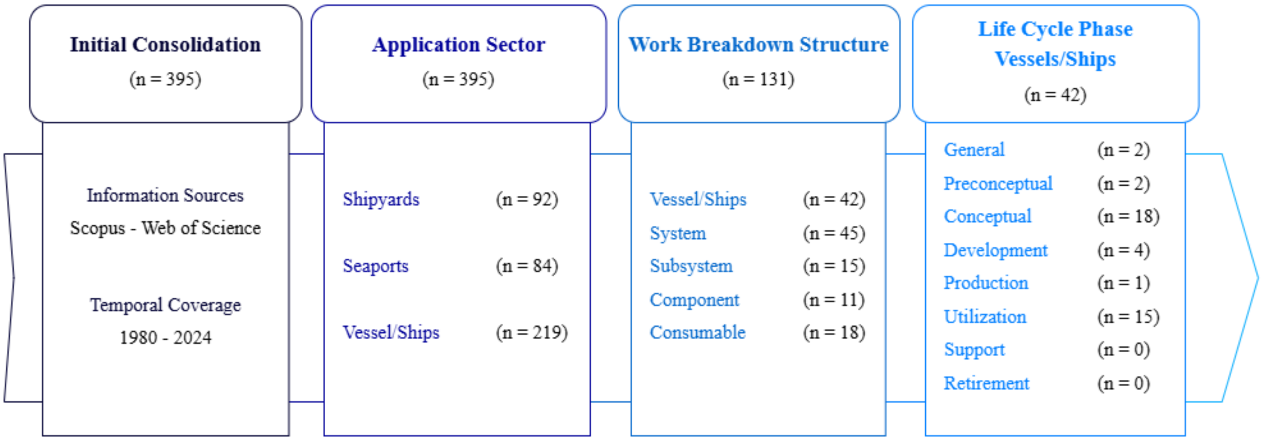

Fig.6: Sample Selection Process

The relatively small number of studies employing MCDM techniques for vessels as SOI underscores the significance of this research area. Figure 7 displays the annual publication count over the analysed period, indicating that it remains unclear whether this represents an emerging field or one with a stable level of academic output. Accordingly, decision-making processes for vessels considered as SOI continue to represent a research domain in its formative stages.

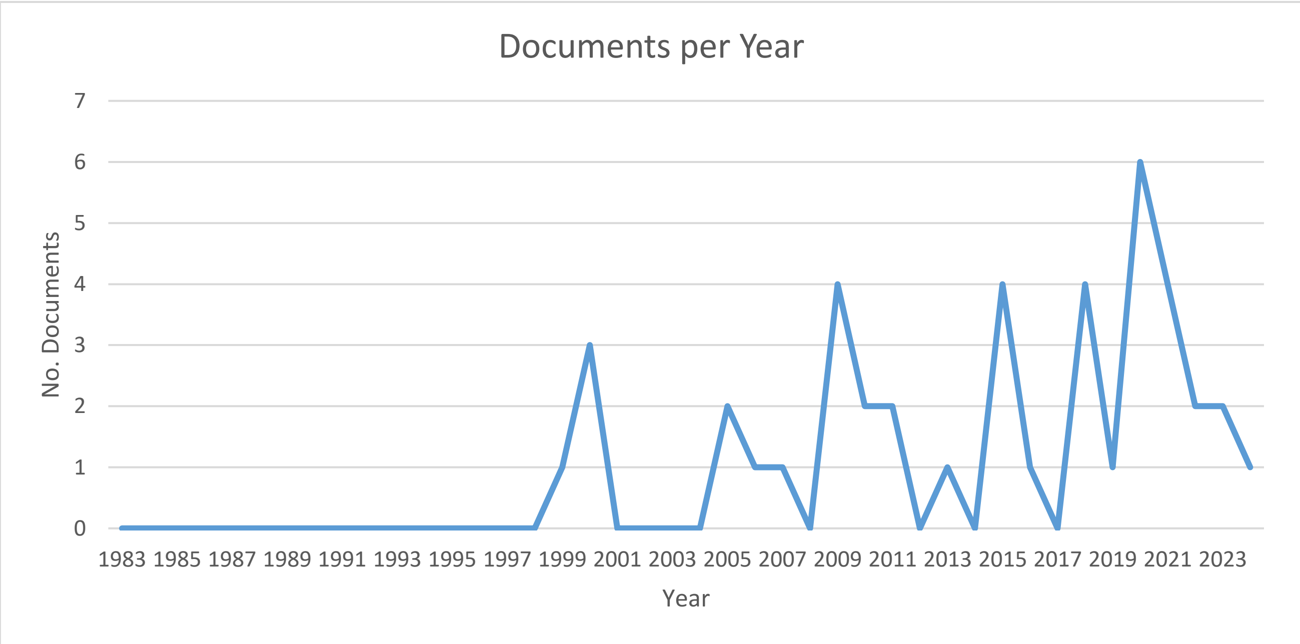

Fig.7: Annual Document Production

The subsequent section presents the findings addressing the research questions, derived from the analysis of the selected sample.

RQ1: According to the ESWBS applied to vessels, at what hierarchical decomposition levels have MCDM techniques been investigated?

Progressing down the ESWBS hierarchy, the selection of suitable technological alternatives becomes critical to ensure that vessels meet established technical requirements. The utilization of MCDM techniques is essential in this context, as it facilitates the verification of compatibility among system attributes and characteristics, which is necessary for the proper functioning of the assembled product [42]. Figure 8 depicts the distribution of studies across the five ESWBS classification levels described in preceding sections.

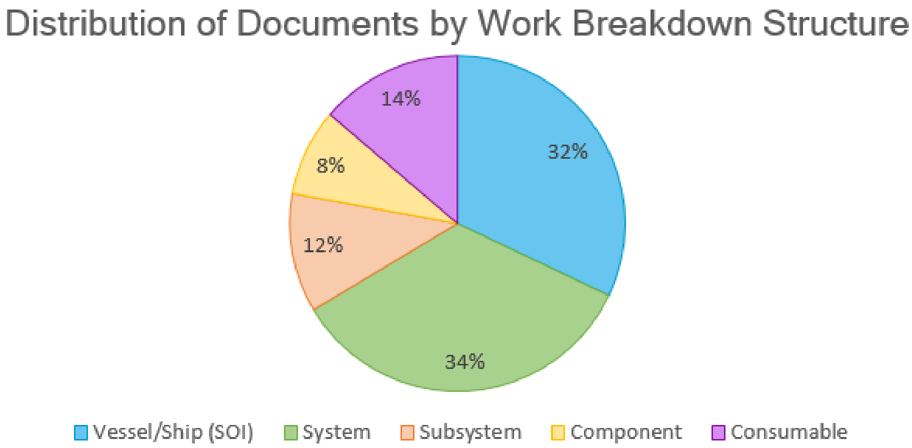

Fig.8: Distribution of Documents According to Hierarchical Decomposition Levels in Vessels

As illustrated in Figures 6 and 8, 32% of the reviewed documents consider vessels as the SOI, with a focus on evaluating sustainability and mitigating environmental impacts during navigation. Approximately 34% of the studies apply MCDM models to select alternatives within specific systems under the ESWBS framework, including hull, propulsion, and navigation systems. This encompasses analyses of different mooring methods, berthing criteria, optimal strategies for naval weapon acquisition, and the assessment of technologies aimed at improving energy efficiency. Additionally, 12% and 8% of the studies address subsystems and components, respectively, evaluating performance, efficiency, and effectiveness at these hierarchical levels [9; 15; 59]. Decision-making concerning consumables, such as coatings, paints, and fuels, is examined with emphasis on emissions produced through usage or degradation [54]. Eighteen documents were identified as relevant, representing 14% of the total sample. A detailed analysis of parts and components was not undertaken due to the high degree of disaggregation and the limited application of MCDM techniques in the available studies.

RQ2: At which stages of the vessel life cycle have studies on multi-criteria decision-making focused?

Decision-making structured around life cycle phases constitutes a critical process for evaluating both current and future impacts of a given technology. This evaluation should commence in the earliest project stages, including the concept and design phases, and extend to the selection of alternatives or the resolution of specific operational issues [89]. Figure 9 illustrates the distribution of documents according to life cycle phases associated with vessel design and selection.

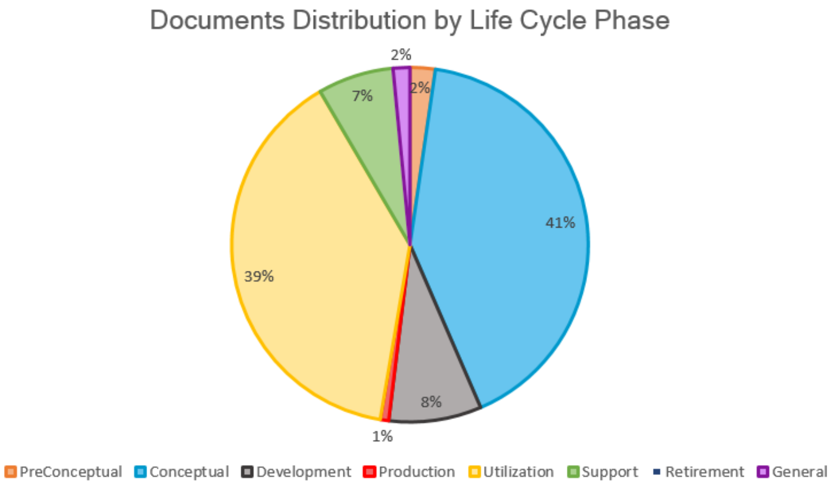

Fig.9: Decision-Making Documents by Lifecycle Phase

Figure 9 presents the distribution of studies across life cycle stages, highlighting a concentration on the conceptual phase (41%) and the utilisation stage (39%). This pattern suggests a preference for applying MCDM in technological decision-making prior to acquisition and for supporting operational decisions involving vessels as SOI. The correspondence between the SE V-model and the life cycle underscores the significance of evaluating alternatives during conceptual design and the necessity of providing support throughout vessel operations. A smaller proportion of studies address the development (8%) and support (7%) phases. This distribution reflects the inherent characteristics of MCDM methods, as the opportunity to modify vessel configurations diminishes progressively from design to construction and operational deployment.

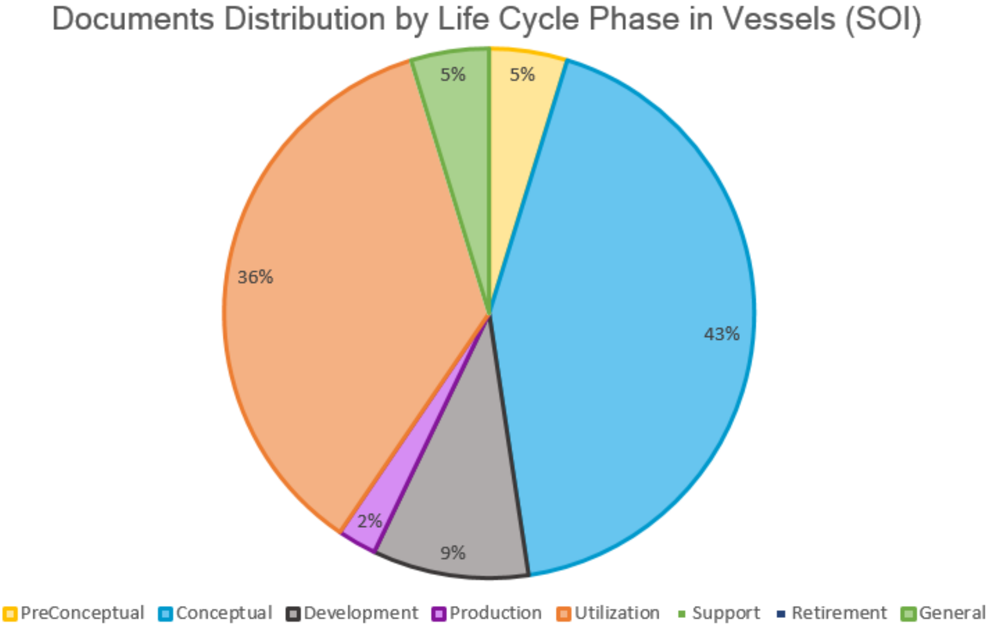

Fig.10: Distribution of Documents by Vessel Lifecycle Phase

The analysis of vessel life cycle phases reveals pronounced attention to the conceptual and utilisation stages, representing 43% and 36% of the literature, respectively, as shown in Figure 10. The predominance of studies in these phases indicates their critical role in supporting vessel design and detailed engineering processes. A noticeable gap exists in research addressing the support phase, likely due to limited information availability during early planning. As project details emerge, support activities increasingly involve external infrastructure, analysis of specific subsystems, evaluation of operational failures, and maintenance planning [2; 23; 26; 28; 55; 69; 90]. Furthermore, studies considering the vessel life cycle from a techno-economic perspective, which quantify costs across operational phases without prioritizing technical performance metrics, are identified [38; 84]. Although methodologically informative, this perspective extends beyond the analytical focus of the present study.

RQ3: What attributes or criteria are commonly considered in the multi-criteria decision-making models applied to the selection, design, and operation of vessels?

Within the analyzed sample, it is evident that models and case studies employ selection criteria to categories vessels and technologies according to preferences, establishing sets of characteristics as attributes. These attributes correspond to alternative parameters that have not yet been systematically classified [66]. Following the SE V-model, TPMs are defined to satisfy KPPs, ensuring precise evaluation of system capabilities. Table 4 subsequently organizes the TPM attributes according to the MOPs identified in the literature review. Based on this framework, the various observed criteria are presented as comparative attributes.

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Table 4
Attributes and Metrics for Vessel Selection

Characteristic (MOPs)	Selection Attributes Identified (TPMs)	Reference
Buoyancy	Draft of Vessel	[27; 32; 61] [31; 37; 56; 58; 85; 86; 92-94; 97]
	Gross Tonnage	[31; 32; 58; 80]
	Load Capacity	[8; 31; 32; 37; 48; 67; 76; 96]
	Depth	[61] [85]
	Dead Weight	[77; 80; 97; 98]
	Crew Accommodation Capacity	[64; 85]
	Propeller Immersion	[76]
	Load Limit	[67]
	Width (Sleeve)	[31; 37; 58; 61; 63; 80; 86; 92-94; 97]
	Overall Length (Length)	[27; 58; 60; 61; 63; 80; 85; 86; 97]
	Stacking Length	[86]
	Longitudinal Prismatic Coefficient	[86]
	Maximum Sectional Area Coefficient	[86]
	Vertical Prismatic Coefficient	[86]
	Strut	[58]
	Medium Draft	[76]
	Trimming	[76]
	Metal Frame Mass	[97] [75; 98]
	Length of Perpendiculars	[97; 99]
	Length Between Perpendiculars	[31; 37; 97]
	Height of Perpendiculars	[97]
	Number of Perpendiculars	[97]
	Length of Pillars	[97]
	Height of Pillars	[97]
	Number of Pillars	[97]
	Hull Shape	[10; 60]
	Weight of Operating Equipment	[76]
	Hull Health Management	[11]
	Height	[37; 63; 98]
Stability	Length of Perpendiculars	[98; 99]
	Height of Perpendiculars	[97]
	Number of Perpendiculars	[97]
	Length of Pillars	[97]
	Height of Pillars	[97]
	Number of Pillars	[97]
	Conditions of Ballast Tanks	[80]
	Work Capacity	[67]
	Work Area on the Roof and Distribution	[10; 60; 77; 85]
	Distribution and Towing Equipment and Cargo Handling	[10]
	Cargo Handling	[32; 92-94]
	Cargo Volume	[31; 76; 99]
	Trimming	[75]
	Available Deck Space	[10]
	Cargo Space	[99]
	Stability at Sea	[10]
	Ballast Systems	[32; 80]
	Boat Breaks	[97]
Structural resistance	Double Bottom Height	[58]
	Width of Double Side	[58]
	Side Hull Plating Thickness	[92-94]
	Thickness of Plating on the Outer or Lower Hull	[32; 92-94]

Table 4 (continued)
Attributes and Metrics for Vessel Selection

Characteristic (MOPs)	Selection Attributes Identified (TPMs)	Reference
	Length of Perpendiculars	[97; 99]
	Height of Perpendiculars	[97]
	Number of Perpendiculars	[97]
	Length of Pillars	[97]
	Height of Pillars	[97]
	Number of Pillars	[97]
	Year of Construction	[31; 80]
	Age of Boat	[92-94]
	Lifespan of a Vessel	[78]
	Optimum and Maximum Bending Moment	[93; 97]
	Hull Shape	[10]
	Vibration Resistance	[8]
	Maintainability	[8; 10; 11; 67; 76]
	Hull Health Management	[11]
	Average Structural Wear in Life Cycle	[38]
Power Generation	Speed	[61] [8; 10; 27; 56; 77; 78; 80; 85; 99]
	Transit Speed	[63; 86]
	Speed of Resistance	[63; 78; 85; 86]
	Sprint Speed	[63; 86]
	Blocking Coefficient	[37; 61; 80]
	Engine Power	[31; 80; 99]
	Propulsion Power	[48; 63; 88]
	Fuel Consumption	[48; 86; 93; 94; 96]
	Fuel Resistance	[20; 63]
	Energy Consumption	[80]
	Type of Propulsion	[48]
	Energy Storage Capacity	[10]
	Traction Power	[10]
	Propeller Health Management	[11]
	Energy System Management	[11; 18]
	Propulsion System Management	[11; 18]
	Electric Power Generation Capacity	[32; 77]
	Electrical System Performance	[77]
Control	Crew	[31]
	Displacement	[37; 63; 85]
	Manoeuvrability	[8; 10; 27; 56; 96]
	Blocking Coefficient	[37; 58; 61]
	Maximum Speed	[10; 31; 63; 80; 86]
	Propeller Health Management	[11]
	Speed Optimization	[11]
	Autopilot	[11]
	Propulsion System Reliability	[32; 92-94]
	Centre of Mass	[77]
Internal Communication	Onboard Information Systems	[17; 77]
Navigation	Traffic Conditions	[27]
	Types of Encounter	[27]
	Environmental Conditions	[27]
	Hours of Operation	[27]
	Navigation Area Type	[27]
	Navigation Status	[56]
	Operation Time	[20; 48; 56]
	Time of Resistance	[20]

Table 4 (continued)
Attributes and Metrics for Vessel Selection

Characteristic (MOPs)	Selection Attributes Identified (TPMs)	Reference
	Level of Replenishment at Sea	[63]
	Operating Range	[56; 86]
	Localization Capability	[56]
	Effective Observation	[27; 56]
	Travel Time	[48]
	Seaworthiness Navigability	[96]
	Autonomy	[20; 63]
	Support Stations	[18; 96]
	Radius of Action Radius	[20; 78]
	Operational Environment Work Environment	[10]
Command and Control	Navigator's Experience	[27]
	Crew Experience	[56]
	Interoperability Level	[63]
External Communication	Radar Sweeping and Action Capability	[63]
	Tactical Diameter	[86]
	Communications Range	[63]
	Radar Type	[63]
	UAV Available on the Vessel	[63]

Selecting appropriate attributes is a highly intricate process due to the interdependence among subsystems and structural components. Certain attributes exert influence across multiple categories, for example, structural elements that simultaneously affect buoyancy, stability, and strength [27; 31; 32; 61; 76]. Similarly, power generation and control are closely linked to the vessel's dimensions and system configurations, thereby impacting both propulsion and manoeuvrability [27; 61]. Beyond purely physical traits, operational factors such as command, control, and communication [27; 63], in addition to external conditions including traffic, environmental influences, and the availability of infrastructure, further shape the selection and intended function of the vessel [17; 27; 48]. Moreover, vessel selection cannot be confined to technical and operational performance; economic, environmental, and social considerations must also be integrated into the evaluation process [71] [13; 33]. Table 5 provides a structured summary of the selection attributes identified in the reviewed sample, organised according to these analytical dimensions.

As previously outlined, the AoA methodology assesses vessel selection through three fundamental dimensions: effectiveness, cost, and risk [71]. Although this study primarily emphasises the application of MCDM for evaluating technical effectiveness, the dimensions of cost and risk remain equally critical. Cost considerations are approached from three perspectives. The first involves measures aimed at minimising expenditures across the vessel's entire life cycle [20; 61; 76; 77]. The second considers opportunities to enhance profitability or operational productivity [97; 98]. The third pertains to investment risk evaluation, addressing financial uncertainties arising during procurement, development, and operational stages [8; 75; 78; 84; 96]. Risk encompasses multiple domains. It includes scheduling and execution risks inherent in ship construction and naval project implementation [10; 20; 32; 38], as well as operational risks associated with occupational safety, accident prevention, and emergency preparedness [6; 11; 17; 97; 98]. Furthermore, it addresses risks related to market readiness and technological maturity, which can influence project feasibility and stakeholder confidence [6; 8; 50; 85]. Together, these assessments enhance stakeholder trust, enable economic efficiencies, and support the attainment of short- and medium-term performance goals. Sustainability is considered across social and environmental dimensions. Socially, emphasis is placed on occupational health and safety, regulatory compliance, and reliable service delivery to the target population [17; 20; 87]. Vessel acquisition is expected to align with regional needs, promoting local welfare and supporting ongoing technology transfer [14].

Table 5
Attributes and Metrics for Vessel Selection

Dimensions	Attributes	References
Economic	Crew Salary	[32; 63; 87; 92-94]
	Purchase Price	[10; 31; 32]
	Fuel Cost	[27; 48; 88; 97; 98]
	Vessel Cost	[58; 61; 78; 85; 97; 99]
	Transportation Cost	[61]
	Annual Cargo	[61]
	EBITDA	[84]
	Crew	[8; 31]
	Fuel Consumption	[27; 31; 72; 76; 88; 92-94; 97; 98]
	Consumables Cost	[8; 92-94]
	Operational Expenses	[8]
	Operation and Maintenance Cost	[6; 10; 17; 20; 31; 48; 63; 75; 78; 84; 98; 99]
	Manufacturing Cost	[17; 50; 75; 98; 99]
	Recycling and Other Costs	[17]
	Construction Cost	[20; 48; 84; 96; 98; 99]
	Acquisition Cost	[20; 38; 77; 78; 85]
	Final Disposal, Dismantling, or Scrapping Cost	[20; 97; 98]
	Modernization Cost	[20]
	Net Present Value (NPV)	[8; 76; 84; 96]
	Capital Expenditure (CapEx)	[8; 84]
	Internal Rate of Return (IRR)	[8; 75; 78]
	Modified Internal Rate of Return (MIRR)	[8]
	Average Freight Rate	[84; 96]
	Return on Investment (ROI)	[8; 80; 84]
	Operational Efficiency	[50]
	Circulation Benefit	[50]
	Financing Possibility	[10]
	Useful Life Subsidies	[77]
	Reduction of Labour and Human Work	[77]
	Overall Life Cycle Cost	[20; 38; 63; 76; 97; 98]
	Supply Cost	[63]
	Insurance Service Cost	[8]
	Productivity	[8]
	Revenue	[97; 98]
	Investment Payback Period	[8]
Environmental	Decommissioning and Recycling	[17]
	Manufacturing	[17]
	Operation	[17] [70]
	Atmospheric Noise	[17] [8]
	Underwater Noise	[8] [88]
	Fuel Type	[96]
	CO_2 Emissions	[6; 8; 48; 96]
	NOx y SOx Emissions	[6; 8; 84; 92-94]
	Life Cycle Equivalent Emissions	[8]
	Environmental Attributes	[50]
	Energy Attributes	[50]
	Resource Attributes	[50]
	Manufacturing Technology	[50]
	Operation Technology	[50]

Table 5 (Continued)
Attributes and Metrics for Vessel Selection

Dimensions	Attributes	References
	Recycling Technology	[50]
	Energy Efficiency Design Index (EEDI)	[84]
	Solid Waste Emission	[70]
	Sewage Emission	[70]
	Pollution from Anti-Fouling Paints	[70]
	Combustion Oils and Bilge Water	[70]
	Ballast Water	[70]
	Fuel Management	[11]
Social	Vessel Environment and Hygiene	[17; 87]
	Comfort and Convenience	[17]
	Service Level and Compliance	[17]
	Recorded Incidents and Accidents	[96]
	Habitability Autonomy	[20]
	Legal Compliance Level	[6; 63; 76; 87]
	Support From Local Businesses	[6]
	Availability of Skilled Personnel	[6]
	Support and Usage Infrastructure	[6; 18]
	Community Awareness and Recognition	[6]
	Company Reliability	[6; 87]
	Promotion System	[87]
	Business Continuity	[87]
	Occupational Health and Safety Conditions	[6; 8; 87]
	Work Schedules	[87]
Risk	Delivery Time	[10; 32]
	Construction and Vessel Delivery Schedule	[20; 38]
	Intact Cargo Delivery	[32]
	Safety Measures	[8; 17]
	Safety Equipment	[17]
	Training and Prevention of Incidents and Accidents	[6; 17]
	Fire Protection	[8; 96]
	Probability of Loss	[78; 80]
	Availability of Auxiliary Vessels	[63]
	Expected and Acceptable Average Spill Flow	[8; 37; 75]
	Damage Survival	[8; 77]
	Energy System Management	[11]
Risk	Management of Propeller Condition, Propulsion System, and Hull	[11]
	Local and Global Safety Measures	[11; 97-99]
	Uncertainty and Technological Maturity	[6; 8; 50; 85]
	System Failure Rate	[38]
	Searchability	[8]
Others	Vessel Type	[27; 29; 56; 78]
	Existence of Specific Operational Equipment	[18; 48; 80]
	Capacity of Specific Operational Equipment	[10; 18; 37; 60; 76; 80]

From an environmental perspective, selection may involve evaluating life cycle phase impacts to ensure compliance with environmental regulations and optimise resource use [33]. However, gaps persist in addressing dismantling and end-of-life stages, particularly regarding micro-level circular economy indicators. Integrating these considerations during the concept and design phases [43] is essential for economic valuation and the planning of industrial strategies aimed at minimising environmental impacts. Finally, a separate category of attributes, designated as “Other,” pertains to the mission and operational purpose of the vessel, defined using MOEs from the earliest stages of project development [13]. The vessel's typology determines the KPPs, which can vary considerably and directly influence system interactions and the target values of performance attributes.

RQ4: What MCDM techniques have been used in the selection, design, optimization, and operation of vessels as Systems of Interest (SOI)?

Given that one of the objectives of this study is to examine the techniques and methodologies employed in the selection, design, optimisation, and operation of vessels, the following section presents the MCDM approaches identified within the study sample. Table 6 summarises the documents that apply MCDM techniques to vessels as SOI, providing details on their specific applications, classifications, methodologies, and the criteria considered in each case.

Table 6
Documents Based on MCDM in Vessels

Reference	Application	Classification	Technique	Approach
[84]	Indicators to Improve the Design of Vessel Fuel Loading	MODM	BoD	Effectiveness-Cost
[38]	Life Cycle Management of Modular Vessels with Test System	MODM	LCC	Effectiveness-Cost
[58]	Multi-Criteria Optimization Applied to Preliminary Vessel Design	MODM	Pareto Tanker Genetic Algorithm (PATANGA)	Effectiveness-Cost
[97]	Multi-Level Decision Support Methodology for the Structural Design of ROPAX Vessels	MODM	SLP, MOPSO, LCC	Effectiveness-Cost
[75; 76]	Optimization of Oil Flow and Cargo Capacity in an AFRAMAX Vessel Design	MODM	Multi-Objective Genetic Algorithm (MOGA)	Effectiveness-Risk
[85]	Conceptual Exploration of DDGXDDG51	MODM	Multi-Objective Genetic Algorithms (MOGA)	Effectiveness-Cost-Risk
[27]	Determining the Domain Size of a Vessel	MADM	AHP FUZZY	Effectiveness-Risk
[17]	Ferry Design Evaluation	MADM	AHP FUZZY	Effectiveness-Cost
[11]	Measurement of Operational Energy Efficiency of Vessels	MADM	AHP FUZZY	Effectiveness
[87]	Selection of the Ideal Vessel for Offshore Watch Officers	MADM	AHP FUZZY	Effectiveness
[20]	Selection of War Vessels	MADM	AHP	Effectiveness-Cost
[52]	Risk Assessment in Naval Projects	MADM	AHP	Effectiveness-Risk
[88]	Selection of Vessel Parking Methods to Reduce Environmental Impacts	MADM	TOPSIS	Effectiveness-Cost
[56]	Selection of Maritime Search and Rescue Units	MADM	PROMETHEE II FUZZY	Effectiveness-Risk
[96]	Selection of New Gas Carrier Vessels	MADM	EVAMIX	Effectiveness-Cost
[80]	Selection of bulk Carrier Vessels	MADM	TOPSIS FUZZY	Effectiveness-Cost
[92]	Vessel Selection in Uncertain Environments	MADM	TOPSIS FUZZY	Effectiveness-Risk
[70]	Marine Pollution Caused by Vessel Operations	MADM	DEMATEL	Effectiveness-Risk
[32]	Uncertainty and Multiple Criteria in Vessel Selection	MADM	Evidential Reasoning (ER)	Effectiveness-Cost
[94]	Evaluation of Second-Hand Liquefied Natural Gas (LNG) Vessels	COMBINED	Delphi and Additive Relative Assessment (ARAS)	Effectiveness-Cost

Table 6 (Continued)
Documents Based on MCDM in Vessels

Reference	Application	Classification	Technique	Approach
[61]	Multi-Objective Design Optimization of Cargo Vessels	COMBINED	NSGA-II - WSM - MADM - Control Function	Effectiveness-Cost
[31]	Selection of Suitable Second-Hand Chemical Tanker Vessels	COMBINED	TOPSIS – WASPAS FUZZY	Effectiveness-Cost
[37]	Selection of Internal Distribution Designs for Vessels	COMBINED	Shannon Entropy and Monte Carlo Simulations	Effectiveness-Cost
[50]	Evaluation of the Green Degree of Vessels	COMBINED	ENTROPIA FUZZY – TOPSIS FUZZY	Effectiveness-Cost
[10]	Evaluation and Selection of a Suitable Tugboat	COMBINED	ENTROPIA FUZZY-TOPSIS FUZZY	Effectiveness-Cost-Risk
[48]	Configuration of Barges in Pushed Convoys in the Amazon	COMBINED	AHP - DEMATEL – ELECTRE	Effectiveness-Cost
[6]	Compliance of Vessels with Regulation 14 of Annex VI of MARPOL	COMBINED	AHP - AHP FUZZY – TOPSIS	Effectiveness-Cost
[67]	Optimization of Subdivisions in Ro-Ro Vessels	COMBINED	MOGA-FRONTIER (PODAs)- (FMAGDM)-TOPSIS	Effectiveness

4.1 PI4.1 Methodological Background of Selection Techniques

The AoA methodological framework provides a structured decision-making process for vessel design, exemplified by its application in the U.S. Navy's CVX programme for the modernisation and enhancement of aircraft carriers through evaluation of technical characteristics [18; 60; 77]. Within this context, the expanded ESWBS was implemented to facilitate detailed analysis of systems and components. Likewise, Rains [78] employed the AoA methodology to evaluate the effectiveness of various naval fleet configurations, taking into account costs, capabilities, and budgetary constraints. Despite AoA's classification of decision criteria into three primary analytical dimensions, the majority of studies adopt a more simplified approach, focusing on selecting criteria directly relevant to the problem without developing an extensive dimensional analysis. The proposed methodology incorporates computational design tools such as MAESTRO, OCTOPUS, and DeMak to model and optimise vessels, specifying variables, objectives, and constraints while employing the finite element method (FEM) to manage complexity. Optimisation of solutions is then conducted using MODM techniques, with subsequent classification via MADM based on client requirements. Finally, the experimental design is evaluated for sensitivity, robustness, and reliability [86; 98; 99].

4.2 PI4.2 Use of MODM Techniques in Vessel Selection

The identified MODM techniques applied in optimising mathematical objective relationships include heuristics such as Multi-Objective Genetic Algorithms (MOGA), Sequential Linear Programming (SLP), Monte Carlo Simulations, Multi-Objective Particle Swarm Optimization (MOPSO), and Benefit of the Doubt (BoD). MOGAs and their variants address multi-objective conflicts through evolutionary principles and are primarily employed in the conceptual design of vessels. They facilitate exploration of the design space and generation of optimal alternatives that balance technical effectiveness, cost, and regulatory risk, thereby supporting decision-making [58; 75; 76]. In contrast, the combined application of MOPSO and SLP, as demonstrated by [95], enables identification of alternatives that minimise life cycle costs while optimising modular vessel design. MODM techniques are not confined to design alone; they are also applied in evaluating composite indicators. For instance, Data Envelopment Analysis (DEA) is utilised to optimise selection values based on risk and cost, supporting the development of cost and environmental impact indicators [87]. These observations indicate that while MOGA techniques dominate vessel design applications, alternative methods exist that enhance resource utilisation and enable prioritisation of criteria during the selection of optimal alternatives.

4.3 PI4.3 Use of MADM Techniques in Vessel Selection

In relation to MADM techniques, multiple extended methodologies have been identified, including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE II), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Evidential Reasoning (ER), and Additive Ratio Assessment (ARAS). These methods are characterised as follows:

AHP is a hierarchical, compensatory method designed to address problems involving multiple criteria and alternatives. It facilitates pairwise comparisons, balancing cognitive effort with solution accuracy. Applications of AHP include selecting a corvette model for the Brazilian Navy and evaluating risks in naval projects, where it proved effective due to its flexibility, structured approach, and ability to generate clear, well-founded solutions [20; 52]. Furthermore, integration of MADM techniques with fuzzy logic allows management of subjectivity in the evaluation of alternatives. FUZZY AHP has been applied across maritime safety, energy efficiency, waterborne transport, and vessel selection, demonstrating effectiveness in decision-making under conditions of incomplete data and subjective judgements [11; 17; 27; 87]. Other MADM methodologies have been employed for vessel evaluation and selection across varied contexts. TOPSIS has been utilised for analysing tugboats in port operations, considering parameters such as costs and emissions. PROMETHEE II has been applied in the selection of search and rescue vessels, accounting for interdependencies among criteria. DEMATEL has been used to identify key factors influencing water pollution, while ARAS has been applied to LNG transport fleet selection, integrating Delphi techniques with fuzzy logic to optimise decision-making [32; 70; 80; 84; 88]. Collectively, these examples indicate that MADM techniques are instrumental in ranking the importance of attributes and evaluating how well alternatives satisfy the assessed criteria. The implementation of fuzzy logic is particularly valuable due to variations in decision-makers' interpretation of linguistic scales.

4.4 PI4.4 Application of Combined Techniques

Given the complexities inherent in integrating multiple criteria for vessel design and selection, several studies have proposed the combination of MCDM techniques. One approach integrates the NSGA-II algorithm to estimate solution density, the Weighted Sum Method (WSM) to convert multiple objectives into a single function, and a hybrid MADM method for optimization, supplemented by a control function to guide the process. This combination aims to reduce construction and transportation costs while maximizing the annual transported cargo, thereby achieving an efficient solution in naval design [61]. Similarly, combinations of Fuzzy Entropy, Fuzzy TOPSIS, and AHP have been applied for diverse objectives, including assessing environmental performance in vessels and selecting tugboats in industrial operations by weighting criteria and optimizing alternative prioritization. The use of AHP in conjunction with DEMATEL has also been demonstrated to analyse causal relationships, while ELECTRE IV has been employed for result validation without reliance on initial weights, particularly in the optimisation of river transport [10; 48; 50]. In addition, AHP and TOPSIS were applied to identify critical barriers and strategies for ensuring vessel compliance with Regulation 14 of Annex VI of the MARPOL Convention in the Gulf of Guinea [6]. The findings emphasised the necessity for infrastructure improvements to support the adoption of Liquefied Natural Gas (LNG) as an alternative fuel, alongside the importance of research and technical training to ensure the safe handling of these fuels.

5. Conclusion

This study provides a systematic literature review on the application of MCDM techniques across the vessel lifecycle, examining their implementation from a systems engineering perspective. From an initial set of 1,296 documents collected from Scopus and Web of Science, 131 met the inclusion criteria, with 42 focusing explicitly on vessels considered as SOI. The analysis addresses four primary research questions. Firstly, MCDM techniques are predominantly applied at the system level, with limited coverage at lower hierarchical levels, including subsystems and components. Secondly, the conceptual design and operational phases of the lifecycle have received the most scholarly attention, whereas support and end-of-life phases remain underexplored. Thirdly, the attributes most frequently considered in vessel selection were identified and classified into technical, economic, social, environmental, and risk dimensions. Lastly, the study evaluated the MCDM techniques applied, highlighting the use of MODM approaches, such as genetic algorithms for optimization, MADM techniques including AHP, TOPSIS, and PROMETHEE for evaluation and selection, and hybrid methods that integrate multiple methodologies to solve complex decision-making problems. Based on these findings, it is recommended that stakeholders in the naval sector, including shipyards, designers, ship owners, and end users, employ MCDM techniques from the early stages of projects. Such approaches facilitate the identification of technically and economically optimal alternatives, enable proactive risk management, and improve efficiency across the entire lifecycle.

However, the study has certain limitations. The document selection was restricted to high-impact databases, namely Scopus and Web of Science, which may have excluded relevant publications from emerging or less-visible sources. Exclusive use of open-access documents further constrained the pool of reviewed studies. The scope of the search was influenced by the chosen keywords, and although effectiveness-related aspects were addressed, coverage of cost and risk analyses was limited, representing opportunities for future research. Future research should prioritise empirical studies to validate optimal models for specific design scenarios. The development and integration of artificial intelligence and simulation tools to complement MCDM methods are encouraged to enhance analytical capabilities under complex and uncertain conditions. Additionally, early-stage incorporation of economic indicators is recommended to support the creation of more sustainable and resilient vessel configurations.

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