

Integrating Master's Voyage Planning Competence and Green Voyage Management to Improve Fuel Efficiency, Emission Performance, and Operational Reliability in Commercial Shipping

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Abstract— The decarbonization of commercial shipping increasingly depends not only on cleaner technologies but also on operational decisions made during voyage planning and execution. However, the contribution of Master-level competence to environmental and operational performance remains insufficiently examined. This study investigates how Master's Voyage Planning Competence (MVPC) improves fuel efficiency, emission performance, and operational reliability through Green Voyage Management (GVM). An explanatory sequential mixed-method design was employed, combining Partial Least Squares Structural Equation Modelling (PLS-SEM) with qualitative validation from experienced maritime professionals. The reported quantitative analysis involved 326 respondents from commercial shipping operations and assessed the relationships among MVPC, GVM, fuel efficiency, emission performance, and operational reliability. The results show that MVPC has a significant positive effect on GVM ($\beta = 0.680$, $p < 0.001$). GVM significantly improves fuel efficiency ($\beta = 0.719$), emission performance ($\beta = 0.699$), and operational reliability ($\beta = 0.731$), with all relationships significant at $p < 0.001$. Mediation analysis further indicates that GVM significantly transmits the effect of MVPC to the three operational outcomes. These findings demonstrate that sustainable shipping performance depends on the effective translation of Master-level competence into environmentally efficient voyage-management practices.

Keywords— Master's Voyage Planning Competence; Green Voyage Management; fuel efficiency; emission performance; operational reliability

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I. INTRODUCTION

Maritime transportation remains a fundamental component of international trade and global supply-chain connectivity, carrying more than 80% of merchandise traded worldwide by volume. Its economic importance, however, is accompanied by substantial environmental and operational challenges arising from fossil-fuel dependence, energy consumption, and greenhouse gas (GHG) emissions. These pressures have intensified as international shipping moves toward increasingly stringent decarbonisation objectives. The 2023 IMO Strategy on Reduction of GHG Emissions from Ships establishes a pathway toward net-zero GHG emissions from international shipping by or around 2050 and reinforces the need for progressive improvements in the carbon intensity of maritime transport [1].

Consequently, environmental performance is no longer peripheral to commercial vessel operation; it has become closely connected with regulatory compliance, energy efficiency, competitiveness, and long-term operational sustainability [2], [27].

The maritime sector has responded to this transition through a broad range of technological and operational initiatives. Research has examined alternative fuels, energy-efficient ship design, propulsion-system improvements, digital energy-management systems, voyage optimisation, weather routing, and artificial intelligence-assisted navigation [4]–[6], [10]–[13]. These developments are essential because technological innovation can significantly improve vessel energy performance and reduce emissions. Nevertheless, the environmental performance achieved during an actual voyage does not depend exclusively on the technical characteristics of a vessel or the availability of advanced optimisation systems. It is also shaped by a sequence of operational decisions involving route selection, voyage appraisal, speed adjustment, weather avoidance, fuel monitoring, navigational risk, and schedule management [8]–[12].

This operational dimension creates an important problem for sustainable shipping. A vessel may be equipped with advanced navigation technologies, decision-support systems, fuel-monitoring tools, and energy-efficiency technologies, yet those resources cannot independently determine how a voyage is conducted. Operational information must still be

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interpreted within changing environmental and commercial conditions, alternatives must be evaluated, and decisions must be implemented without compromising navigational safety. The performance of technological systems is therefore inseparable from the competence of maritime professionals responsible for using them [14], [15], [18]. This is particularly relevant at the management level, where the Master has responsibility for integrating navigational safety, voyage efficiency, operational continuity, and regulatory requirements.

According to IMO Model Course 7.01 for Masters and Chief Mates, management-level nautical competence encompasses advanced voyage planning, navigation management, risk assessment, operational decision-making, bridge resource management, and the effective use of available navigational information [3]. These competencies imply substantially more than procedural knowledge. Voyage planning requires the Master to assess route alternatives, interpret meteorological and oceanographic conditions, anticipate navigational hazards, evaluate operational constraints, establish contingency arrangements, coordinate bridge resources, and revise the voyage when circumstances change. Consequently, the quality of voyage planning can influence not only navigational safety but also sailing distance, speed profile, fuel consumption, voyage duration, schedule stability, and ultimately environmental performance [5], [9], [12].

Despite this operational significance, maritime competence research has historically been dominated by a safety perspective. Human-factor studies have demonstrated the importance of situational awareness, communication, decision-making, teamwork, leadership, and bridge resource management in accident prevention and operational reliability [14]–[17]. Such research has substantially improved understanding of the human element in maritime safety. However, considerably less attention has been directed toward the role of management-level nautical competence in achieving energy-efficiency and decarbonisation objectives. The Master is therefore widely recognised as a critical safety decision-maker, but the same professional has not been investigated to the same extent as a potential contributor to sustainable vessel operation.

A parallel limitation can be observed in the green-shipping literature. Green-shipping studies have expanded rapidly in response to international emission-reduction targets and have identified several operational measures capable of reducing fuel consumption and emission intensity [4]–[9]. Slow steaming, route optimisation, weather routing, speed management, energy-efficient navigation, and systematic fuel monitoring can provide efficiency improvements without requiring immediate replacement of existing vessels [7]–[9], [24]. Such measures are especially relevant during the transition toward low- and zero-carbon fuels because the global fleet cannot be transformed instantaneously and existing vessels must continue to improve their environmental performance [26], [27].

Nevertheless, many studies conceptualise voyage optimisation primarily as a computational, engineering,

or technological problem. Mathematical algorithms determine efficient routes, data-driven models predict fuel consumption, artificial intelligence supports optimisation, and digital platforms provide increasingly sophisticated operational recommendations [10]–[13], [18], [20], [28]. These technologies can improve the quality and quantity of information available to shipboard decision-makers, but they do not eliminate the requirement for professional judgement. Recommended speeds or routes may have to be reconsidered because of traffic density, weather deterioration, navigational hazards, port requirements, machinery limitations, cargo considerations, or safety constraints. Consequently, the effectiveness of a technically optimal recommendation ultimately depends on whether it can be interpreted and implemented appropriately within the operational context of the voyage.

This interaction between technological capability and human judgement provides the basis for *Green Voyage Management (GVM)*. In this study, GVM represents the systematic integration of environmental and energy-efficiency considerations into voyage planning and voyage execution. Its principal practices include efficient route selection, speed management, fuel-consumption monitoring, energy-conscious navigation, and emission-reduction-oriented operational decisions [7], [21]. GVM therefore differs from a purely technological optimisation tool. It represents an operational management process through which information, technology, professional competence, environmental objectives, and navigational constraints are transformed into actual voyage decisions.

The central research problem is that the mechanism through which Master-level competence contributes to green operational outcomes remains insufficiently established. Existing studies show that operational measures can reduce energy consumption [4], [5], [9], that digital optimisation can support efficient navigation [10]–[13], and that human competence affects maritime safety and reliability [14]–[17]. However, these research streams remain only partially connected. As a result, there is limited empirical explanation of whether stronger Master's Voyage Planning Competence (MVPC) facilitates Green Voyage Management and whether this managerial mechanism is subsequently associated with fuel efficiency, emission performance, and operational reliability.

Three interrelated research gaps emerge from this problem. The first is *a technology–human integration gap*. Existing voyage-optimisation research has concentrated strongly on algorithms, predictive modelling, digitalisation, and decision-support technologies, while comparatively less attention has been devoted to the competence of the maritime decision-maker who evaluates and implements those recommendations [10], [11], [18], [28]. This creates a risk of treating optimisation as if technically superior information automatically generates superior operational performance.

The second is *a sustainability–competence gap*. Research concerning maritime competence has primarily examined safety, human error, accident prevention,

bridge resource management, and human reliability [14]–[17]. Yet the competencies required for safe voyage management—including situational assessment, judgement, planning, resource coordination, and adaptive decision-making—may also be relevant to fuel and emission performance. The contribution of these competencies to sustainable shipping has not been examined as systematically as their contribution to safety.

The third is a *management-level integration gap*. Green-shipping research frequently examines environmental strategies at the ship, fleet, technological, or organisational level [7], [19], [21]. Fewer studies explicitly connect an individual management-level capability—particularly the Master’s voyage planning competence—with vessel-level environmental and operational outcomes. This limits understanding of how sustainability strategies are translated from corporate objectives and technological capabilities into decisions made during individual voyages.

Addressing these gaps requires a socio-technical interpretation of sustainable shipping. From this perspective, improved environmental performance is produced neither by human competence nor by technological resources in isolation. Technologies provide information and operational possibilities, while competent maritime professionals evaluate these possibilities within safety, environmental, commercial, and regulatory constraints. Sustainable performance therefore depends on the interaction between technical capability and managerial decision-making [17], [21]. In such a framework, MVPC can be conceptualised as a strategic human capability, whereas GVM represents the operational mechanism through which that capability is applied.

Accordingly, this study investigates the relationship between *Master’s Voyage Planning Competence, Green Voyage Management, Fuel Efficiency, Emission Performance, and Operational Reliability in commercial shipping*. The principal objective is to determine whether MVPC is positively associated with the implementation of GVM and whether GVM subsequently contributes to improved fuel efficiency, emission performance, and operational reliability. The study also examines whether GVM functions as a mediating mechanism through which Master-level voyage planning competence is translated into these operational outcomes.

The proposed relationship between MVPC and GVM is based on the premise that Masters with stronger competencies in voyage appraisal, passage planning, risk-informed decision-making, situational awareness, and bridge resource management should be better positioned to incorporate environmental and energy-efficiency considerations into voyage decisions [3], [17]. Competence enables the Master not merely to access information but to assess its relevance, resolve competing operational priorities, and adapt voyage plans as conditions change. Therefore, the first hypothesis is formulated as follows:

H1: Master’s Voyage Planning Competence has a positive and significant effect on Green Voyage Management.

GVM is expected to influence fuel efficiency because route selection, speed management, weather adaptation, voyage monitoring, and fuel-consumption control affect the energy required to complete a voyage [9], [10], [20]. Better integration of these practices should reduce avoidable energy consumption and improve the utilisation of fuel during vessel operation. Therefore:

H2: Green Voyage Management has a positive and significant effect on Fuel Efficiency.

Fuel use and vessel emissions are closely related because conventional marine energy consumption remains a major source of operational GHG emissions. Operational strategies that reduce unnecessary energy consumption or improve carbon efficiency should therefore contribute to improved emission performance [4], [5], [26]. Accordingly:

H3: Green Voyage Management has a positive and significant effect on Emission Performance.

Green voyage practices may also affect the reliability of vessel operations. Effective route appraisal, anticipatory weather assessment, appropriate speed management, continuous voyage monitoring, and better coordination of operational resources can support voyage consistency and reduce avoidable deviations and disruptions [8], [22], [23]. Consequently:

H4: Green Voyage Management has a positive and significant effect on Operational Reliability.

Finally, professional competence does not necessarily produce measurable sustainability benefits merely because it exists. Its contribution depends on how that competence is applied through operational practice. GVM is therefore proposed as the mechanism through which MVPC is transformed into improved fuel, emission, and reliability outcomes [17], [21]. The mediation hypothesis is expressed more precisely in relation to the three dependent variables:

H5: Green Voyage Management significantly mediates the relationships between Master’s Voyage Planning Competence and (a) Fuel Efficiency, (b) Emission Performance, and (c) Operational Reliability.

The *novelty of this study* lies in positioning Master’s Voyage Planning Competence as an antecedent of Green Voyage Management rather than treating maritime competence solely as a safety-related construct. The proposed model links a management-level human capability to three distinct vessel-performance outcomes through an explicit operational mechanism. This differs from technology-centred approaches in which sustainable performance is explained mainly by vessel design, alternative energy, optimisation algorithms, or digital systems, and it extends human-factor research beyond conventional safety outcomes. In this way, the study connects maritime competence, green operational management, and sustainable transport performance within one empirical framework.

The study consequently offers three related contributions. Theoretically, it extends maritime sustainability research by integrating management-level nautical competence into the explanation of green operational performance. Methodologically, it evaluates GVM as a mediating construct connecting MVPC with fuel efficiency, emission performance, and operational

reliability rather than assuming a direct equivalence between competence and sustainability performance. Practically, the framework can inform shipping companies, maritime education and training institutions, and regulators regarding the need to integrate energy-efficient navigation, carbon-aware voyage planning, and environmentally responsible operational decision-making into management-level professional development [17], [27].

Sustainable shipping therefore cannot be understood solely as the outcome of cleaner fuels, more efficient machinery, or increasingly sophisticated digital technologies. These resources create the technical potential for improved performance, but their operational value depends on the decisions through which they are applied. By examining the pathway from Master's Voyage Planning Competence through Green Voyage Management to fuel efficiency, emission performance, and operational reliability, this study places the maritime professional directly within the decarbonisation and operational-performance discourse and provides a human-centred complement to prevailing technology-oriented approaches.

. II. LITERATURE REVIEW

2.1 Master's Voyage Planning Competence as a Management-Level Maritime Capability.

The increasing complexity of commercial shipping has expanded the professional role of the ship Master beyond conventional navigational control. At the management level, the Master is required to integrate navigational safety, voyage execution, risk assessment, operational coordination, regulatory compliance, and effective utilisation of bridge resources. IMO Model Course 7.01 for Masters and Chief Mates identifies management-level competence in areas that include voyage planning, navigation management, operational decision-making, risk evaluation, and bridge resource management [3]. These competencies provide the professional foundation through which the Master supervises and adapts vessel operations under changing maritime conditions.

Within this study, *Master's Voyage Planning Competence (MVPC)* refers to the integrated capability of the Master to appraise a voyage, develop and evaluate a passage plan, interpret relevant operational information, assess navigational and environmental conditions, make risk-informed decisions, and coordinate available bridge resources. MVPC is therefore broader than the technical ability to prepare a route. It represents a management-level capability through which navigational information is transformed into operational decisions.

Voyage planning is particularly important because it occurs before and throughout voyage execution. Initial appraisal requires evaluation of the intended route, expected environmental conditions, navigational constraints, operational requirements, and available information. Passage planning translates this appraisal into a structured navigational plan, while execution and

monitoring require the bridge team to assess whether actual operating conditions remain consistent with the assumptions used during planning. When conditions change, the Master must determine whether speed, route, timing, or other elements of the voyage should be adjusted.

This decision process has consequences beyond navigational safety. Route choice influences sailing distance and exposure to adverse conditions, while speed decisions influence both voyage duration and energy demand. Weather interpretation can affect whether a vessel maintains, alters, or delays an intended passage. Fuel considerations may also become relevant when evaluating operational alternatives. Therefore, voyage planning constitutes an interface between navigational, economic, environmental, and operational objectives [5], [9], [12].

The human-factor literature provides further justification for treating MVPC as an operational capability. Maritime operations are conducted within socio-technical systems in which human judgement interacts continuously with navigation equipment, communication systems, organisational procedures, and external environmental conditions. Situational awareness, communication, teamwork, professional judgement, and decision-making have been identified as important determinants of maritime operational performance and safety [14]–[17]. Although this literature has traditionally concentrated on accident prevention and human reliability, the same competencies are relevant when Masters must evaluate competing voyage alternatives under conditions of uncertainty.

Digitalisation does not remove this human requirement. Data-driven energy-management systems, weather-routing platforms, optimisation algorithms, and navigation decision-support technologies can process large quantities of information and provide increasingly sophisticated recommendations [10]–[13], [18]. However, the availability of a recommendation is not equivalent to its operational implementation. A Master may need to reconcile a recommended route or speed with navigational hazards, deteriorating weather, traffic conditions, machinery capability, port schedules, cargo requirements, or safety considerations. Professional competence therefore remains necessary to determine when and how technology-generated information should be incorporated into a voyage decision.

For this reason, MVPC is conceptualised in the present research as a *strategic human capability* rather than merely an individual technical skill. Its relevance lies in the ability to integrate information, assess operational consequences, and convert professional knowledge into appropriate voyage-management decisions. This conceptualisation extends the traditional treatment of maritime competence from predominantly safety-related outcomes toward a broader role in sustainable and efficient ship operation [17].

2.2 Green Voyage Management in Sustainable Commercial Shipping

Green shipping has become an increasingly important component of maritime transport management because

the sector is required to improve energy efficiency and reduce greenhouse gas emissions while continuing to provide reliable transport services. The 2023 IMO Strategy on Reduction of GHG Emissions from Ships reinforces the transition toward lower-carbon maritime transportation and emphasises the need for improved operational as well as technological performance [1]. Industry and policy discussions similarly recognise that operational measures remain important while alternative fuels, new propulsion technologies, and fleet renewal develop progressively [2], [26], [27].

Within this context, *Green Voyage Management (GVM)* can be understood as the systematic incorporation of energy-efficiency and environmental considerations into the planning, execution, and monitoring of a vessel voyage. The concept draws upon established green-shipping practices and operational measures that include route optimisation, speed management, weather-responsive navigation, fuel monitoring, energy-efficient vessel operation, and emission-reduction practices [7]–[9], [21], [24].

GVM differs from a narrow interpretation of voyage optimisation. Voyage optimisation can refer primarily to the mathematical determination of a preferred route or operational profile. GVM, by contrast, represents the managerial process through which environmental efficiency is incorporated into actual voyage decisions. It therefore includes not only identifying potentially efficient alternatives but also evaluating whether those alternatives can be implemented safely and consistently within the vessel's operational context.

Route optimisation is one component of this process. Efficient route selection can reduce unnecessary distance or avoid conditions that would lead to excessive energy use. Speed management is another important component because changes in operational speed affect fuel consumption and voyage duration [4], [5], [9]. Fuel monitoring contributes by enabling the bridge and operational management team to recognise deviations in consumption and evaluate whether corrective action is required. Environmental operation extends these activities by incorporating emission-related considerations into day-to-day navigation and voyage execution.

Previous green-shipping research has established the relevance of these operational measures, but much of the literature has approached them through technological, engineering, or optimisation perspectives [10]–[13], [18], [20]. Such research is essential, yet it does not fully explain how technologically generated information becomes an operational decision. GVM therefore provides an appropriate intermediate construct because it represents the practical managerial application of environmental and efficiency objectives during a voyage. In the present study, GVM is consequently conceptualised as the mechanism linking professional capability with measurable vessel outcomes. A Master may possess substantial navigational knowledge and decision-making capability, but sustainability improvements require that this competence be expressed through practices such as efficient routing, adaptive

speed management, fuel-conscious navigation, and emission-aware operational decisions.

2.3 Master's Voyage Planning Competence and Green Voyage Management

The relationship between MVPC and GVM is central to the proposed research model. Green voyage practices require decisions that frequently involve multiple and potentially competing considerations. For example, an energy-efficient route may need to be evaluated against weather exposure, navigational safety, traffic conditions, voyage schedules, or operational constraints. Similarly, reducing or adjusting speed may affect estimated arrival time and service requirements. Effective implementation therefore requires more than environmental awareness; it requires professional competence capable of integrating environmental objectives with the wider requirements of vessel operation.

Masters with stronger voyage appraisal competence should be better able to evaluate route alternatives and identify operational conditions that may affect energy utilisation. Strong passage-planning capability should support the development of voyage plans that account for navigational constraints and operational efficiency. Risk-based decision-making enables the Master to judge whether a proposed efficiency measure remains acceptable under prevailing conditions. Situational awareness and bridge resource management further support the continuous monitoring and adaptation necessary when conditions change during voyage execution [3], [14]–[17].

This relationship can also be interpreted through a socio-technical perspective. Technology supplies navigation data, weather information, fuel-consumption information, route alternatives, and other operational inputs. Human competence determines how these inputs are interpreted, prioritised, and implemented. Therefore, the environmental value of voyage-support technology depends partly on the capability of the decision-maker responsible for converting technical information into operational action.

The proposed relationship does not imply that the Master acts independently of the organisation, vessel technology, or external regulatory environment. Rather, it suggests that management-level competence represents one important enabling capability within the broader maritime system. Where relevant systems and information are available, stronger MVPC should improve the ability to integrate green considerations into voyage-management practices.

Accordingly, the first hypothesis is:

H1: Master's Voyage Planning Competence has a positive and significant effect on Green Voyage Management.

2.4 Green Voyage Management and Fuel Efficiency

Fuel efficiency represents a critical element of commercial shipping performance because fuel consumption affects both operating expenditure and environmental impact. Vessel energy use is influenced by several interacting conditions, including speed, sailing distance, weather, loading conditions, vessel

characteristics, and operational decisions [8], [9], [12]. Although some determinants cannot be controlled directly during a voyage, operational management can influence how the vessel responds to them.

Green Voyage Management is expected to improve fuel efficiency through coordinated control of route, speed, voyage monitoring, and fuel utilisation. Route-management decisions can reduce unnecessary sailing or exposure to operational conditions that increase resistance and energy demand. Speed-management decisions influence the amount of power required during voyage execution. Continuous fuel monitoring can help identify deviations from intended energy-performance patterns and support corrective operational decisions.

The importance of operational measures is particularly relevant for existing commercial fleets. Major technological modifications or transitions to alternative fuels require investment, infrastructure, and time, whereas operational improvements can often be implemented within the current vessel-management system [5], [24], [27]. This does not mean that operational measures can substitute completely for technological decarbonisation, but they provide an important pathway for improving energy performance during the transition.

Previous studies cited in the manuscript indicate that route optimisation, speed control, data-informed navigation, and voyage management can influence fuel consumption [9], [10], [12], [20]. GVM integrates these individual practices into a broader managerial construct. Consequently, a higher level of GVM should be associated with more efficient use of fuel during commercial vessel operations.

Therefore:

H2: Green Voyage Management has a positive and significant effect on Fuel Efficiency.

2.5 Green Voyage Management and Emission Performance

Emission performance represents a distinct environmental outcome within the proposed framework. Although it is closely associated with fuel efficiency, it should not be treated as conceptually identical. Fuel efficiency concerns the utilisation of energy or fuel during operation, whereas emission performance concerns the environmental consequences associated with that operation, including CO₂-related performance and carbon intensity.

The distinction is relevant because international maritime regulation increasingly evaluates shipping not only through fuel use but also through carbon-performance indicators. The introduction of instruments such as the Energy Efficiency Existing Ship Index and Carbon Intensity Indicator has reinforced attention to the relationship between vessel operation and carbon performance. The broader IMO decarbonisation framework likewise places progressive reductions in shipping emissions at the centre of maritime sustainability policy [1], [26].

GVM can contribute to improved emission performance because many operational measures that reduce avoidable fuel consumption also reduce the emissions associated with conventional vessel energy

use. Speed optimisation, efficient routing, voyage monitoring, and energy-conscious navigation can therefore support lower emission intensity when effectively implemented [4], [5], [9], [24].

However, the theoretical importance of GVM extends beyond the mechanical connection between fuel consumption and emissions. GVM incorporates environmental considerations directly into operational decision-making. This means that emission performance becomes an explicit management objective rather than an incidental consequence of cost-oriented fuel saving. The distinction supports the sustainability orientation of the construct and reflects the changing role of voyage management under decarbonisation requirements.

The proposed framework therefore expects vessels characterised by stronger implementation of green voyage practices to demonstrate better emission-related performance.

Accordingly:

H3: Green Voyage Management has a positive and significant effect on Emission Performance.

2.6 Green Voyage Management and Operational Reliability

Operational reliability is the third performance outcome examined in this study. In commercial maritime transportation, reliability relates to the ability to maintain stable, predictable, and consistent voyage operations. It can include schedule reliability, voyage consistency, operational continuity, and the capacity to respond effectively to conditions that could otherwise disrupt planned operations [22], [23].

Operational reliability is important because commercial shipping cannot pursue environmental efficiency independently of service requirements. A voyage strategy that reduces fuel use but consistently produces unacceptable delays or operational instability would be difficult to sustain commercially. Sustainable voyage management therefore requires balancing environmental efficiency with the need for predictable transport performance.

GVM can support operational reliability through improved planning and anticipatory decision-making. Systematic voyage appraisal may enable Masters to identify potential operational constraints earlier. Weather-responsive routing may reduce exposure to conditions that could produce major deviations. Adaptive speed management can help balance fuel efficiency with arrival requirements, while continuous monitoring allows deviations from the voyage plan to be detected and managed.

The relationship also illustrates why green operations should not necessarily be interpreted as a trade-off against commercial performance. Environmental efficiency and operational reliability can potentially reinforce each other when both are incorporated into an integrated voyage-management process. More systematic planning, information utilisation, and operational monitoring can simultaneously reduce unnecessary energy use and improve voyage consistency [7], [8], [22], [23].

The manuscript therefore treats operational reliability as an independent outcome rather than combining it with

emission performance. This distinction is conceptually important: emission performance reflects environmental effectiveness, whereas operational reliability reflects continuity and consistency of commercial ship operations.

Thus:

H4: Green Voyage Management has a positive and significant effect on Operational Reliability.

2.7 Green Voyage Management as a Mediating Mechanism

The theoretical contribution of the proposed model becomes clearer when Green Voyage Management is considered as a mediator rather than merely another independent variable. Competence is an underlying capability, whereas fuel efficiency, emission performance, and operational reliability are operational outcomes. A theoretical mechanism is therefore required to explain how the capability of the Master is translated into those outcomes.

MVPC by itself does not necessarily reduce fuel consumption or emissions. A Master may possess strong knowledge, judgement, and voyage-planning capability, but measurable performance improvements arise only when those capabilities influence actual operational decisions. GVM represents this application stage. It converts professional capability into actions involving route optimisation, speed management, fuel monitoring, efficient navigation, and environmentally responsible voyage decisions.

This capability–practice–performance sequence distinguishes the proposed framework from models that assume a simple direct relationship between professional competence and sustainability performance. The present study instead argues *that competence enables practice, and practice influences performance*. The mediator therefore has both theoretical and managerial relevance. For fuel efficiency, the mechanism can be expressed as MVPC → better green-voyage decisions → more efficient fuel utilisation. For emission performance, the proposed mechanism is MVPC → environmentally informed voyage management → improved carbon-related operational performance. For operational reliability, the mechanism is MVPC → more systematic and adaptive voyage management → greater voyage consistency and operational stability.

The mediation structure is also consistent with the socio-technical orientation of the study. Human capability does not operate separately from technical systems and operational procedures. Instead, competence interacts with information, technology, and operational conditions through managerial practices. GVM captures this interaction and therefore provides the theoretical bridge between the human element and sustainable vessel performance.

The mediation hypothesis is consequently formulated separately for each dependent outcome:

H5a: Green Voyage Management significantly mediates the relationship between Master's Voyage Planning Competence and Fuel Efficiency.

H5b: Green Voyage Management significantly mediates the relationship between Master's Voyage Planning Competence and Emission Performance.

H5c: Green Voyage Management significantly mediates the relationship between Master's Voyage Planning Competence and Operational Reliability.

2.8 Theoretical Integration and Research Framework

Based on the preceding literature, the proposed framework integrates three research domains that have often developed separately: management-level maritime competence, green-shipping operational management, and vessel-performance outcomes. Maritime competence research provides the human-capability foundation of the model [3], [14]–[17]. Green-shipping and maritime-decarbonisation research provides the operational practices through which environmental objectives are incorporated into ship operation [1], [4]–[9], [21], [24], [26], [27]. Maritime transport-performance literature provides the basis for evaluating efficiency and operational reliability [22], [23].

The framework therefore follows a sequential logic. *Master's Voyage Planning Competence is the antecedent capability; Green Voyage Management is the operational mechanism; Fuel Efficiency, Emission Performance, and Operational Reliability are the resulting performance dimensions*. This structure explicitly recognises that sustainable maritime performance requires interaction among professional judgement, operational management, and environmental objectives.

The proposed framework also clarifies the scientific novelty of the study. Existing technology-oriented research explains how routing algorithms, data-driven systems, optimisation tools, and energy technologies can improve vessel performance [10]–[13], [18], [20]. Existing human-factor research explains how competence and decision-making influence safety and operational reliability [14]–[17]. The present research connects these perspectives by examining whether management-level voyage-planning competence enables environmentally oriented operational practice and whether that practice subsequently contributes to three distinct performance outcomes.

Accordingly, the research model consists of five latent constructs: *Master's Voyage Planning Competence (MVPC)*, *Green Voyage Management (GVM)*, *Fuel Efficiency (FE)*, *Emission Performance (EP)*, and *Operational Reliability (OR)*. MVPC is modelled as the antecedent of GVM, while GVM is modelled as the direct predictor of FE, EP, and OR and as the mediator of the relationships between MVPC and each performance outcome.

This integrated structure provides the theoretical basis for the subsequent empirical analysis and directly reflects the study objective of determining how Master-level voyage planning competence can contribute to more efficient, lower-emission, and operationally reliable commercial shipping through Green Voyage Management

III. METHOD

3.1 Research Design and Approach

This study adopted an explanatory sequential mixed-method design to examine how Master's Voyage Planning Competence (MVPC) contributes to sustainable shipping performance through Green Voyage Management (GVM). The research framework combines a quantitative phase based on Partial Least Squares Structural Equation Modelling (PLS-SEM) with a qualitative phase involving maritime professionals.

The mixed-method approach was selected because the relationships examined in this study involve both measurable structural relationships and operational decision-making processes. The quantitative phase was used to evaluate the relationships among MVPC, GVM,

Fuel Efficiency (FE), Emission Performance (EP), and Operational Reliability (OR). The qualitative phase was intended to provide contextual interpretation of how management-level maritime competence is translated into environmentally efficient voyage practices.

The research process consisted of three sequential stages. First, the conceptual model and measurement constructs were developed from IMO Model Course 7.01, maritime competence literature, green-shipping studies, and maritime transport-performance research [3], [7], [17], [21]. Second, the proposed relationships were evaluated quantitatively using PLS-SEM. Third, qualitative validation was incorporated through semi-structured interviews with experienced maritime professionals to support interpretation of the quantitative relationships.

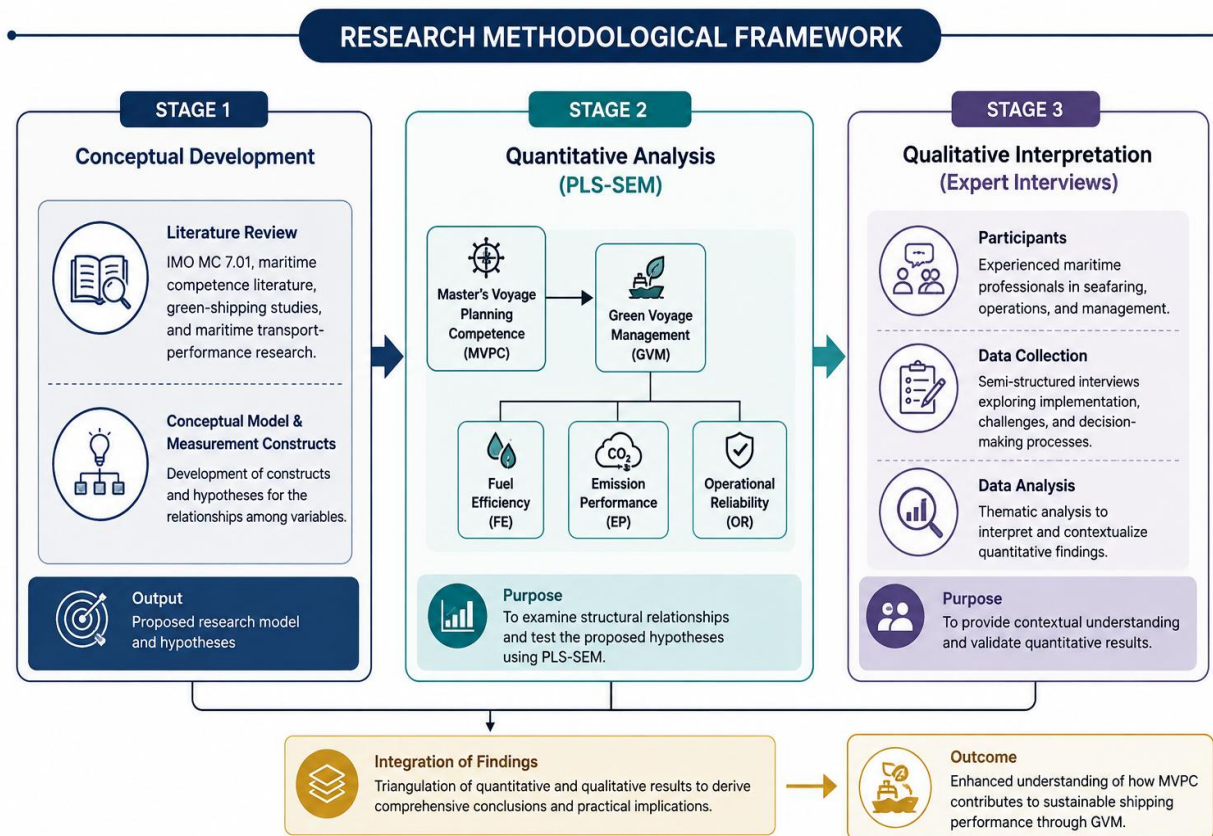


Figure 1. Research Methodological Framework

Figure 1 presents the overall research sequence from literature review and conceptual development to quantitative analysis, qualitative interpretation, and integration of the findings.

3.2 Conceptual Framework and Structural Model

The conceptual framework integrates three complementary perspectives. The first is the management-level maritime competency framework derived primarily from IMO Model Course 7.01, which identifies voyage planning, navigation management, risk assessment, operational decision-making, and bridge resource management as important competencies for Masters and Chief Mates [3].

The second perspective is Green Voyage Management. Green-shipping literature indicates that operational decisions involving route optimisation, speed

management, fuel monitoring, and energy-efficient navigation can influence vessel environmental performance [7], [21].

The third perspective concerns maritime operational performance. In this study, performance is represented by three distinct constructs: Fuel Efficiency, Emission Performance, and Operational Reliability. These constructs were maintained separately because they represent different dimensions of vessel performance. Fuel Efficiency reflects energy utilisation, Emission Performance reflects carbon-related environmental outcomes, and Operational Reliability reflects voyage consistency and operational stability [22], [23].

The structural model proposes that MVPC functions as an antecedent capability that enables GVM. GVM subsequently influences FE, EP, and OR. In addition to these direct relationships, GVM is examined as a

mediating mechanism through which Master-level voyage planning competence is translated into the three operational outcomes.

The proposed relationships are expressed as follows:

H1: $MVPC \rightarrow GVM$

H2: $GVM \rightarrow FE$

H3: $GVM \rightarrow EP$

H4: $GVM \rightarrow OR$

H5a: $MVPC \rightarrow GVM \rightarrow FE$

H5b: $MVPC \rightarrow GVM \rightarrow EP$

H5c: $MVPC \rightarrow GVM \rightarrow OR$

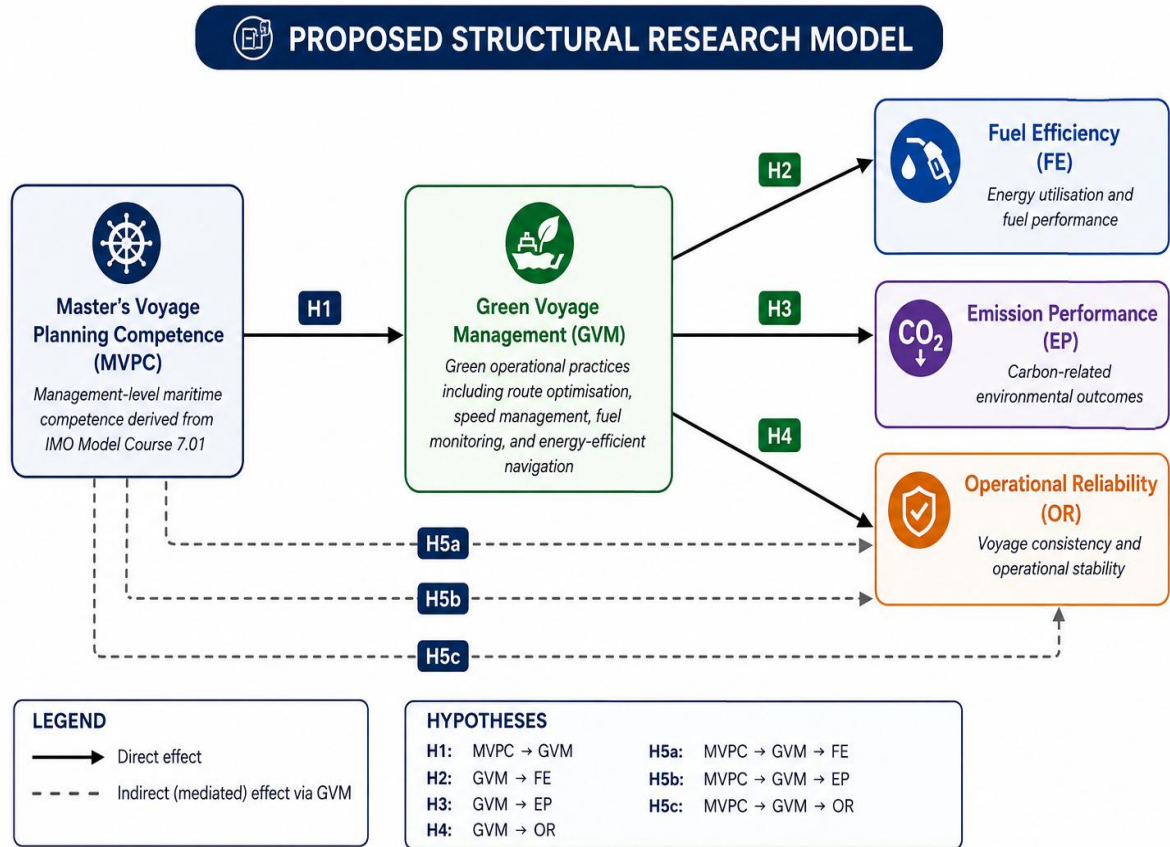


Figure 2. Proposed Structural Research Model

The structural model therefore represents a capability–practice–performance sequence in which professional competence enables green operational practices and those practices subsequently influence vessel-performance outcomes.

3.3 Research Constructs and Measurement Development

The model consists of five latent constructs: Master's Voyage Planning Competence, Green Voyage Management, Fuel Efficiency, Emission Performance, and Operational Reliability.

MVPC was operationalised through management-level voyage-planning capabilities derived from the maritime competency framework. Its principal dimensions include voyage appraisal, passage planning, operational decision-making, situational awareness, and bridge resource management. These dimensions represent the Master's ability to evaluate voyage conditions, prepare and adapt navigational plans, assess operational risks, and coordinate bridge resources [3].

GVM was operationalised through environmentally oriented voyage-management practices. The principal dimensions include route optimisation, speed management, fuel monitoring, energy-efficient navigation, and emission-reduction-oriented operational practices [1], [5]–[7], [21].

FE represents the efficient utilisation of fuel during vessel operation and was measured through indicators associated with reduction in fuel consumption and improved energy utilisation. EP reflects carbon-related environmental performance and includes indicators associated with CO₂ reduction and carbon intensity. OR reflects the stability and consistency of commercial voyage operations and includes schedule reliability and voyage consistency.

All measurement items were evaluated using a five-point Likert scale ranging from 1 = *strongly disagree* to 5 = *strongly agree*.

TABLE 1.
RESEARCH CONSTRUCTS AND MEASUREMENT DIMENSIONS

Construct	Dimension	Operational Indicators
Master's Voyage Planning Competence (MVPC)	Voyage appraisal	Route evaluation; environmental assessment
	Passage planning	Navigation planning; contingency planning
	Decision-making	Operational judgement; risk-informed decision-making
	Situational awareness	Monitoring and interpretation of voyage conditions
Green Voyage Management (GVM)	Bridge resource management	Communication; teamwork; coordination
	Route optimisation	Efficient route selection
	Speed management	Energy-efficient speed decisions
	Fuel monitoring	Consumption monitoring and control
	Energy-efficient navigation	Integration of efficiency considerations into navigation
Fuel Efficiency (FE)	Environmental operation	Emission-reduction-oriented practices
Emission Performance (EP)	Energy utilisation	Fuel-consumption efficiency
Operational Reliability (OR)	Carbon performance	CO ₂ -related performance; carbon intensity
	Operational stability	Schedule reliability; voyage consistency

The measurement structure was designed to maintain conceptual separation among the five constructs while reflecting the capability–practice–performance logic of the proposed model.

3.4 Population, Respondents, and Sampling

The target population consisted of maritime professionals involved directly or indirectly in commercial voyage planning and ship operational management. The respondent groups comprised:

- Masters;
- Chief Officers;
- Deck Officers; and
- shore-based fleet or operation managers.

These professional groups were selected because their roles involve navigation planning, voyage execution, ship-operation supervision, or operational decision-making relevant to the constructs examined in this study [3], [17].

A purposive sampling approach was applied because participation required professional knowledge and operational experience related to commercial shipping, navigation management, and voyage planning. The manuscript reports **326 valid observations** used in the quantitative analysis. These observations form the analytical dataset used for the subsequent measurement- and structural-model evaluation.

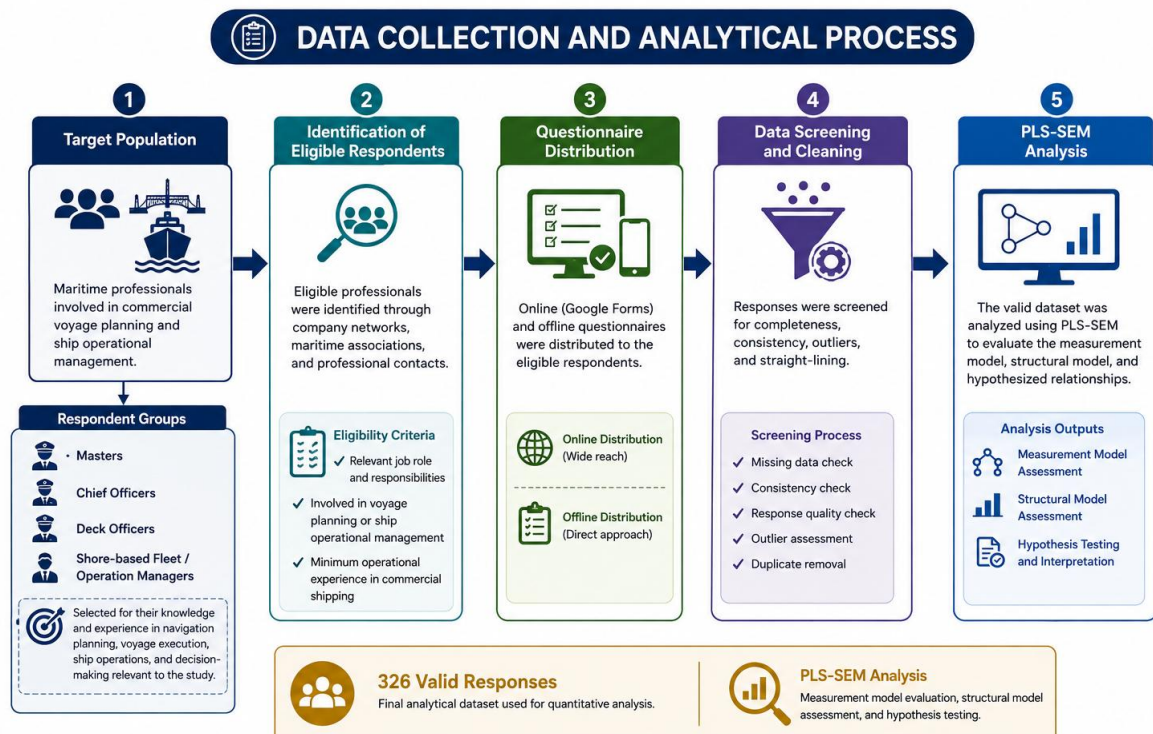


Figure 3. Data Collection and Analytical Process

Figure 3 illustrates the sequence used in the quantitative phase, beginning with identification of eligible maritime professionals, followed by questionnaire administration, data screening, preparation of the valid dataset, and PLS-SEM analysis.

3.5 Research Instrument

The questionnaire was developed from internationally recognised maritime competency requirements and the green-shipping and maritime-performance literature. The instrument was organised into four main components.

The first component collected respondent characteristics, including professional position, years of maritime experience, vessel type, and operational background.

The second component measured MVPC through items addressing voyage appraisal, passage planning, navigation management, operational decision-making, situational awareness, and bridge resource management.

The third component measured GVM through items concerning route optimisation, energy-conscious speed management, fuel monitoring, energy-efficient navigation, and emission-reduction-oriented voyage practices.

The fourth component measured the three outcome constructs: Fuel Efficiency, Emission Performance, and Operational Reliability.

Before the main analytical phase, the questionnaire was reviewed by maritime professionals to assess whether the measurement items were relevant to the intended maritime operational context and adequately represented the constructs under investigation.

3.6 Quantitative Data Analysis

The quantitative data were analysed using Partial Least Squares Structural Equation Modelling with SmartPLS. PLS-SEM was selected because the study examines multiple latent constructs, predictive structural relationships, and mediation effects within an integrated model.

The analysis consisted of two principal stages: assessment of the measurement model and assessment of the structural model.

3.6.1 Measurement Model Assessment

The measurement model was evaluated to determine whether the indicators adequately represented their respective latent constructs.

Indicator reliability was assessed using outer loadings. Indicator loadings of approximately 0.70 or higher were regarded as evidence that an item contributed adequately to its intended construct.

Internal consistency reliability was evaluated using Cronbach's alpha and Composite Reliability. Values greater than 0.70 were used as the criterion for satisfactory construct reliability.

Convergent validity was assessed using Average Variance Extracted (AVE). An AVE value greater than 0.50 indicated that a construct explained more than half of the variance in its indicators.

Discriminant validity was specified for assessment through the Fornell-Larcker criterion and the

Heterotrait-Monotrait ratio (HTMT). These procedures were used to evaluate whether each latent construct was empirically distinguishable from the other constructs in the model.

3.6.2 Structural Model Assessment

Following establishment of the measurement model, the structural relationships were evaluated using:

- path coefficients (β);
- coefficient of determination (R^2);
- effect size (f^2);
- predictive relevance (Q^2); and
- statistical significance based on bootstrapping.

A bootstrapping procedure using **5,000 resamples** was specified to estimate the significance of the hypothesised path coefficients.

The coefficient of determination (R^2) was used to evaluate the proportion of variance in each endogenous construct explained by its predictor or predictors. Predictive relevance was evaluated using Q^2 , with positive values interpreted as evidence that the model possessed predictive relevance for the corresponding endogenous construct.

Effect size (f^2) was included in the analytical framework to evaluate the contribution of individual predictor constructs to the explanatory power of the model.

3.7 Mediation Analysis

The mediating role of Green Voyage Management was evaluated through indirect-effect analysis. Three specific indirect relationships were examined:

$MVPC \rightarrow GVM \rightarrow FE$

$MVPC \rightarrow GVM \rightarrow EP$

$MVPC \rightarrow GVM \rightarrow OR$

The mediation analysis was designed to determine whether Master's Voyage Planning Competence contributes to operational performance through the implementation of Green Voyage Management rather than assuming that professional competence directly produces fuel, emission, or reliability outcomes.

Bootstrapped indirect effects were used to evaluate the statistical significance of the three mediation pathways.

3.8 Qualitative Validation and Interpretation

The qualitative component was designed to provide contextual understanding of the quantitative findings through semi-structured interviews with experienced maritime professionals, including Masters, Chief Officers, and maritime operation managers.

The interview framework focused on four principal themes:

1. the incorporation of fuel-efficiency considerations into voyage planning;
2. the influence of environmental considerations on navigational decisions;
3. operational challenges associated with implementing Green Voyage Management; and
4. the role of management-level competence development in supporting sustainable commercial shipping.

The qualitative material was intended to support

interpretation of the statistical relationships by explaining how competence, environmental considerations, and operational constraints interact during real voyage-management decisions.

The quantitative and qualitative components were subsequently integrated at the interpretation stage to examine whether the statistical relationships were consistent with the professional experiences and operational reasoning of maritime practitioners

IV. RESULTS AND DISCUSSION

4.1 Data Characteristics and Respondent Profile

The analytical dataset reported in this study consisted of 326 observations representing maritime professionals involved in commercial shipping operations. Respondents comprised Masters, Chief Officers, Deck Officers, and shore-based operation managers. The sample represented different levels of professional responsibility and maritime experience, allowing the model to be evaluated across personnel involved in voyage planning, navigation management, and vessel operational decision-making.

TABLE 2.
RESPONDENT CHARACTERISTICS (N = 326)

Characteristic	Category	Frequency	Percentage (%)
Position	Master	72	22.1
	Chief Officer	94	28.8
	Deck Officer	112	34.4
	Shore Operation Manager	48	14.7
Years of Maritime Experience	<5 years	36	11.0
	5–10 years	91	27.9
	11–20 years	124	38.0
	>20 years	75	23.1
Vessel Type	Container	102	31.3
	Bulk Carrier	87	26.7
	Tanker	76	23.3
	Passenger/Other	61	18.7

The professional composition of the sample is relevant to the research objective. Masters and Chief Officers represented 50.9% of respondents, while Deck Officers accounted for a further 34.4%. These groups operate within the navigational and bridge-management environment in which voyage-planning decisions are developed, evaluated, and implemented.

The experience profile also indicates substantial professional exposure. A total of 61.1% of respondents reported more than ten years of maritime experience, consisting of 38.0% with 11–20 years and 23.1% with more than 20 years. The sample therefore contains a substantial proportion of personnel with prolonged exposure to navigation management and commercial ship operations.

Respondents were also distributed across several commercial vessel categories: container vessels

accounted for 31.3%, bulk carriers for 26.7%, tankers for 23.3%, and passenger or other vessel categories for 18.7%. This distribution provides operational diversity within the reported dataset because voyage characteristics, service requirements, fuel-consumption patterns, and navigational constraints can differ among vessel types.

4.2 Measurement Model Assessment

Before examining the structural relationships, the measurement model was evaluated for internal consistency reliability and convergent validity. The revised model maintains five distinct latent constructs: Master's Voyage Planning Competence (MVPC), Green Voyage Management (GVM), Fuel Efficiency (FE), Emission Performance (EP), and Operational Reliability (OR).

TABLE 3.
CONSTRUCT RELIABILITY AND CONVERGENT VALIDITY

Construct	Cronbach's Alpha	Composite Reliability	AVE
Master's Voyage Planning Competence	0.921	0.941	0.764
Green Voyage Management	0.934	0.952	0.798
Fuel Efficiency	0.902	0.928	0.721
Emission Performance	0.915	0.939	0.757
Operational Reliability	0.908	0.932	0.734

All constructs demonstrated high internal consistency. Cronbach's alpha values ranged from 0.902 to 0.934, while Composite Reliability values ranged from 0.928 to 0.952. These values exceed the 0.70 criterion specified in

the methodological framework, indicating satisfactory reliability of the constructs.

Convergent validity was also supported by the reported Average Variance Extracted values. AVE ranged from 0.721 for Fuel Efficiency to 0.798 for Green Voyage

Management, with every construct exceeding the 0.50 criterion. These results indicate that the indicators associated with each construct share sufficient variance to represent their intended latent variable.

Green Voyage Management exhibited the highest AVE (0.798) and Composite Reliability (0.952), suggesting particularly strong internal coherence among the indicators used to represent route optimisation, speed management, fuel monitoring, energy-efficient navigation, and environmentally oriented operational practices.

Figure 4. Measurement Model Structure

Figure 4 presents the measurement structure linking Master's Voyage Planning Competence with Green

Voyage Management and the three separate performance outcomes. Maintaining Fuel Efficiency, Emission Performance, and Operational Reliability as independent constructs is important because each represents a different dimension of commercial shipping performance.

4.3 Structural Model Assessment

Following assessment of construct reliability and convergent validity, the structural model was evaluated using the coefficient of determination (R^2), predictive relevance (Q^2), path coefficients, and bootstrapping significance tests. The reported analysis used 5,000 bootstrap resamples.

TABLE 4.
STRUCTURAL MODEL EVALUATION

Endogenous Construct	R^2	Q^2
Green Voyage Management	0.462	0.351
Fuel Efficiency	0.517	0.382
Emission Performance	0.489	0.367
Operational Reliability	0.534	0.401

The R^2 value for GVM was 0.462, indicating that MVPC accounted for 46.2% of the variance in the reported Green Voyage Management construct. This result is important because it suggests that management-level voyage-planning competence is meaningfully associated with the extent to which green voyage practices are implemented.

For the three performance outcomes, the reported R^2 values were 0.517 for Fuel Efficiency, 0.489 for Emission Performance, and 0.534 for Operational Reliability. Among these outcomes, Operational Reliability demonstrated the highest explained variance. The Q^2 values were positive for all endogenous constructs, ranging from 0.351 to 0.401. Within the

analytical framework specified in this study, these positive values indicate predictive relevance for GVM, FE, EP, and OR. Operational Reliability again exhibited the highest reported Q^2 value (0.401), followed by Fuel Efficiency (0.382), Emission Performance (0.367), and Green Voyage Management (0.351).

Taken together, the R^2 and Q^2 results indicate that the proposed capability–practice–performance model possesses meaningful explanatory and predictive relevance within the reported dataset.

4.4 Direct-Effect Hypothesis Testing

The four direct hypotheses were evaluated using standardised path coefficients, t-values, and p-values.

TABLE 5.
DIRECT-EFFECT RESULTS

Hypothesis	Relationship	β	t-value	p-value	Result
H1	MVPC $\rightarrow$ GVM	0.680	14.52	<0.001	Supported
H2	GVM $\rightarrow$ Fuel Efficiency	0.719	16.84	<0.001	Supported
H3	GVM $\rightarrow$ Emission Performance	0.699	15.71	<0.001	Supported
H4	GVM $\rightarrow$ Operational Reliability	0.731	17.26	<0.001	Supported

The relationship between MVPC and GVM was positive and statistically significant ($\beta = 0.680$, $t = 14.52$, $p < 0.001$), supporting H1. This result indicates that stronger voyage-planning competence is associated with stronger implementation of Green Voyage Management. GVM also showed positive and statistically significant relationships with all three performance outcomes. The relationship with Fuel Efficiency was $\beta = 0.719$ ($t = 16.84$, $p < 0.001$), supporting H2. The relationship with Emission Performance was $\beta = 0.699$ ($t = 15.71$, $p < 0.001$), supporting H3. The relationship with Operational Reliability was $\beta = 0.731$ ($t = 17.26$, $p < 0.001$), supporting H4.

Among the three downstream paths, the strongest coefficient occurred between GVM and Operational Reliability. This result is noteworthy because it suggests that environmentally oriented voyage-management practices are associated not only with fuel and emission outcomes but also with the consistency and stability of commercial vessel operations.

4.5 Mediation Analysis

The central theoretical proposition of this study is that competence becomes operationally valuable when it is translated into Green Voyage Management practices. This proposition was assessed through three specific indirect relationships.

TABLE 6.
MEDIATION-EFFECT RESULTS

Hypothesis	Indirect Relationship	Indirect Effect	t-value	p-value	Result
H5a	MVPC → GVM → Fuel Efficiency	0.489	11.26	<0.001	Supported
H5b	MVPC → GVM → Emission Performance	0.475	10.84	<0.001	Supported
H5c	MVPC → GVM → Operational Reliability	0.497	11.79	<0.001	Supported

All three reported indirect effects were positive and statistically significant. The indirect relationship between MVPC and Fuel Efficiency through GVM was 0.489 ($t = 11.26$, $p < 0.001$). The indirect effect on Emission Performance was 0.475 ($t = 10.84$, $p < 0.001$), while the indirect effect on Operational Reliability was 0.497 ($t = 11.79$, $p < 0.001$).

The largest indirect effect was therefore observed for Operational Reliability, followed by Fuel Efficiency and Emission Performance. The results support the theoretical proposition that GVM acts as an important mechanism linking Master-level competence with operational performance.

The mediation results also provide a more precise interpretation of the role of competence. Professional competence should not be interpreted as directly equivalent to reduced fuel consumption or lower emissions. Rather, competence provides the capability to evaluate information and make operational decisions, while GVM represents the practical application of that capability through route selection, speed management, fuel monitoring, and environmentally conscious navigation.

4.6 Discussion of Findings

4.6.1 Master's Voyage Planning Competence as an Enabler of Green Voyage Management

The significant MVPC → GVM relationship ($\beta = 0.680$) provides empirical support for the study's principal human-capability argument. Maritime sustainability research has traditionally placed strong emphasis on technological pathways such as alternative fuels, efficient ship design, voyage-optimisation algorithms, data-driven energy-management systems, and digital navigation technologies [4]–[6], [10]–[13], [18]. These technologies are essential components of maritime decarbonisation, but the present finding indicates that implementation of environmentally efficient voyage practices is also associated with the competence of the professional responsible for interpreting and applying operational information.

This distinction is important. Digital optimisation systems can identify route or speed alternatives, but actual vessel operation occurs within a dynamic environment involving weather, traffic, safety requirements, machinery conditions, commercial schedules, and navigational constraints. At the management level, the Master must evaluate whether an optimisation recommendation remains operationally appropriate under prevailing conditions. The finding therefore supports a socio-technical interpretation in which technology provides decision support while competence provides the professional judgement required to transform information into action.

The result also extends the role traditionally assigned to maritime competence. Previous human-factor research cited in the manuscript has primarily connected competence, situational awareness, communication, and decision-making with safety and human reliability [14]–[17]. The present model extends that logic toward sustainable operation by positioning voyage-planning competence as a capability associated with environmentally oriented operational management.

The novelty is consequently not the assertion that the Master is important to ship operation; this is already well established. The contribution lies in demonstrating within the proposed model that management-level voyage-planning competence is statistically connected to a specific sustainability-oriented managerial construct—Green Voyage Management—which subsequently relates to fuel, emission, and reliability outcomes.

4.6.2 Green Voyage Management and Fuel Efficiency

The significant relationship between GVM and Fuel Efficiency ($\beta = 0.719$) supports the proposition that voyage-level operational management is strongly associated with energy performance. This finding is consistent with the literature cited in the manuscript concerning slow steaming, route optimisation, weather routing, speed management, and operational energy efficiency [4], [5], [9], [20], [24].

The finding is operationally important because fuel consumption is not determined solely by vessel design or machinery characteristics. Voyage execution also influences energy demand. A longer route, unsuitable speed profile, unnecessary deviation, or ineffective response to weather conditions can increase energy consumption even when the vessel itself is technically efficient. Conversely, systematic route appraisal, adaptive speed decisions, voyage monitoring, and fuel-awareness can support more efficient use of available energy.

GVM therefore represents an operational layer between technological potential and realised energy performance. A technically efficient vessel may not realise its full efficiency potential if voyage decisions are poorly managed. Similarly, a vessel operating with existing technology may still obtain operational improvements when voyage decisions are systematically oriented toward energy efficiency.

This distinction is particularly relevant to the transition toward low-carbon shipping. Technological renewal and alternative fuels require substantial investment and cannot be implemented simultaneously across every existing vessel. Operational improvement therefore remains an important complementary pathway during the transition period [24], [27].

The result should not be interpreted as demonstrating that GVM can replace technological decarbonisation.

Instead, it indicates that the effectiveness of sustainable shipping strategies depends on combining technological improvements with competent operational management.

4.6.3 Green Voyage Management and Emission Performance

The GVM → Emission Performance relationship was also positive and statistically significant ($\beta = 0.699$). This result supports the environmental dimension of the proposed model and indicates that stronger implementation of green voyage practices is associated with better reported emission performance.

Fuel Efficiency and Emission Performance are closely related but conceptually distinct. Fuel Efficiency concerns the utilisation of energy, whereas Emission Performance concerns the environmental consequences of vessel operation, including CO₂-related performance and carbon intensity. Maintaining these constructs separately allows the model to distinguish economic-operational efficiency from environmental performance. The finding is consistent with the manuscript's broader decarbonisation argument. Operational measures that reduce unnecessary fuel consumption can contribute to emission reduction, particularly where vessels continue to rely on conventional fuels [4], [5], [26]. However, GVM also introduces an explicit environmental orientation into voyage decision-making. In this sense, carbon performance is not treated merely as an incidental consequence of reducing fuel expenditure; it becomes part of the operational criteria considered when voyages are planned and executed.

This distinction has managerial significance. When environmental considerations become embedded in route selection, speed management, voyage monitoring, and energy-conscious navigation, environmental responsibility moves from a strategic policy statement at company level toward operational implementation aboard individual vessels.

The finding therefore supports one of the central arguments of the study: maritime decarbonisation requires not only cleaner technologies but also the capability to translate environmental objectives into routine operational decisions.

4.6.4 Green Voyage Management and Operational Reliability

The strongest direct relationship in the structural model was found between GVM and Operational Reliability ($\beta = 0.731$), and OR also exhibited the highest reported R^2 (0.534) and Q^2 (0.401). This is one of the most consequential findings of the study because it challenges the assumption that environmentally responsible voyage practices necessarily impose an operational penalty.

The reported relationship suggests instead that green voyage practices may coexist with, and potentially support, operational stability. Route appraisal, weather-responsive planning, adaptive speed management, and continuous voyage monitoring are environmental-efficiency practices, but they are also elements of disciplined voyage management. Better anticipation of voyage conditions may reduce avoidable deviations,

while more systematic monitoring can support timely operational adjustments.

Operational Reliability therefore provides an important bridge between environmental sustainability and commercial performance. Shipping companies are required to reduce environmental impact without compromising the consistency of transport services. If green voyage practices are positively associated with both environmental outcomes and operational reliability, sustainability need not be conceptualised purely as a cost or constraint. It can also be considered part of a broader operational-performance strategy.

Nevertheless, the result should be interpreted within the limits of the reported model. The statistical association does not establish that every green operational measure will improve schedule reliability under every condition. Masters may still encounter situations in which safety, weather, port requirements, or other operational constraints require decisions that differ from the most fuel-efficient alternative. The relevance of competence lies precisely in managing such trade-offs.

4.6.5 The Mediating Role of Green Voyage Management

The mediation results constitute the most important theoretical finding of the study. GVM significantly mediated the relationships between MVPC and Fuel Efficiency (indirect effect = 0.489), Emission Performance (0.475), and Operational Reliability (0.497).

These findings clarify **how** Master's Voyage Planning Competence is connected with sustainable operational performance. Competence represents a capability, but a capability cannot improve fuel or emission performance unless it changes operational behaviour. GVM supplies this missing mechanism.

The theoretical sequence can therefore be expressed as:

Professional capability → Green operational practice → Vessel-performance outcome.

This capability–practice–performance mechanism represents a more precise explanation than a simple competence–performance relationship. A Master may possess extensive knowledge, experience, situational awareness, and decision-making competence, but these attributes generate sustainability benefits only when they are incorporated into route appraisal, speed decisions, fuel monitoring, energy-efficient navigation, and other operational practices.

The mediation findings consequently connect two bodies of literature that are often treated separately. Human-factor research emphasises competence and decision-making [14]–[17], while green-shipping research emphasises technology, operational measures, and environmental management [7], [9], [21]. GVM provides the conceptual bridge between them.

The largest indirect effect was observed for Operational Reliability (0.497). This result reinforces the interpretation that the value of competent green voyage management extends beyond environmental indicators. When professional capability is translated into structured green operational practices, the resulting benefits are associated with both sustainability and operational consistency.

4.6.6 Scientific Novelty of the Integrated Model

The principal novelty of this study lies in the *integration of a management-level human competence construct with green voyage practices and three distinct vessel-performance outcomes within a single structural framework.*

First, the study moves beyond a predominantly technology-centred interpretation of sustainable shipping. Previous research discussed in the manuscript has examined alternative fuels, vessel energy efficiency, artificial intelligence, weather routing, data-driven optimisation, and decision-support systems [4]–[13], [18], [20]. The present framework does not reject these technological approaches. Instead, it identifies the Master's competence as a complementary capability that influences how technical information and operational opportunities are converted into voyage decisions.

Second, the model extends maritime competence research beyond its conventional safety orientation. Competence, situational awareness, decision-making, communication, and bridge resource management have traditionally been examined primarily in relation to accident prevention and safe operation [14]–[17]. This study broadens the performance domain by associating management-level voyage-planning competence with environmentally oriented operational practice.

Third, the model introduces GVM as the transformation mechanism between capability and outcome. This mediation structure is theoretically important because it avoids assuming that competence directly creates sustainability. Instead, competence enables operational practices, and those practices are associated with measurable performance.

Fourth, the study evaluates sustainability through more than one dependent variable. Fuel Efficiency represents energy utilisation, Emission Performance represents environmental performance, and Operational Reliability represents commercial-operational stability. The model therefore treats sustainable shipping as a multidimensional objective rather than reducing it exclusively to emission reduction.

The resulting contribution is a socio-technical interpretation of maritime sustainability in which *technology determines what is technically possible, organisational systems provide the operating framework, and professional competence influences how those possibilities are translated into actual voyage decisions.*

4.6.7 Implications for Shipping Management

The findings have implications for shipping companies because they indicate that decarbonisation strategies should address both vessel technology and operational capability. Investment in fuel-monitoring platforms, weather-routing systems, voyage-optimisation tools, and digital decision support may provide limited benefit if shipboard decision-makers are insufficiently prepared to integrate these tools into operational planning.

Competency-development programmes for Masters and deck officers should therefore connect traditional voyage-planning requirements with energy and environmental performance. Training should strengthen

the ability to evaluate route alternatives, interpret efficiency information, balance speed and schedule requirements, monitor fuel-consumption performance, and incorporate environmental objectives without compromising navigational safety.

The strong relationship between GVM and Operational Reliability is particularly relevant for commercial management. Environmental management need not be separated from operational performance management. Voyage-planning procedures can instead be designed to evaluate fuel, emissions, reliability, and safety simultaneously.

Shore-based fleet managers also have an important role because Masters operate within organisational and commercial constraints. Effective GVM requires coordination between shipboard and shore-based decision-makers concerning voyage instructions, arrival requirements, fuel-performance expectations, environmental targets, and operational priorities.

4.6.8 Implications for Maritime Education and Training

The findings also support a broader interpretation of management-level maritime education. IMO Model Course 7.01 provides a competence foundation for voyage planning, navigation management, risk assessment, and bridge resource management [3]. Within the sustainability transition, these capabilities can be linked more explicitly with energy-efficient navigation and environmental performance.

Maritime education and training institutions may therefore consider strengthening learning outcomes related to carbon-aware voyage planning, fuel-performance interpretation, energy-efficient navigation, environmental decision-making, and the operational use of voyage-optimisation technologies.

Such integration should not replace established navigation and safety competencies. Rather, sustainability should be incorporated into the same professional decision-making framework. The Master of a modern commercial vessel must increasingly evaluate safety, operational, commercial, and environmental information simultaneously.

4.7 Overall Interpretation

Taken together, the results support the proposed capability–practice–performance framework. MVPC was significantly associated with GVM, and GVM was significantly associated with Fuel Efficiency, Emission Performance, and Operational Reliability. The three indirect effects further support GVM as the mechanism through which Master-level competence is connected with the reported vessel-performance outcomes.

The central contribution of the findings is therefore not merely that competent Masters or green practices are beneficial. The more important conclusion is that sustainable commercial shipping appears to depend on the *translation of professional competence into structured green operational practice.*

This interpretation provides a human-centred complement to technological approaches to maritime decarbonisation. Cleaner fuels, more efficient ships, digitalisation, and optimisation technologies remain

essential, but their operational effectiveness depends partly on the capability of maritime professionals to interpret information, balance competing requirements, and implement appropriate voyage decisions. Sustainable shipping should therefore be approached as a socio-

V. CONCLUSION

This study examined how Master's Voyage Planning Competence (MVPC) contributes to sustainable commercial shipping performance through Green Voyage Management (GVM), with particular attention to Fuel Efficiency (FE), Emission Performance (EP), and Operational Reliability (OR). The findings support the proposed capability–practice–performance framework and indicate that management-level voyage-planning competence is an important antecedent of environmentally oriented voyage management.

The reported structural results show that MVPC has a positive and significant relationship with GVM ($\beta = 0.680$, $p < 0.001$). This finding indicates that stronger competence in voyage appraisal, passage planning, operational judgement, situational awareness, and bridge resource management is associated with stronger implementation of green voyage practices. The result extends the conventional interpretation of Master-level competence beyond navigational safety by demonstrating its relevance to sustainable operational management.

GVM was also positively and significantly associated with all three performance outcomes. The effect on Fuel Efficiency was $\beta = 0.719$, the effect on Emission Performance was $\beta = 0.699$, and the effect on Operational Reliability was $\beta = 0.731$, with all relationships significant at $p < 0.001$. Among these relationships, the strongest effect was observed for Operational Reliability. These findings indicate that Green Voyage Management is associated not only with improved energy and environmental performance but also with greater consistency and stability of commercial vessel operations.

The mediation analysis further clarifies the mechanism underlying these relationships. GVM significantly mediated the relationship between MVPC and Fuel Efficiency (indirect effect = 0.489), Emission Performance (indirect effect = 0.475), and Operational Reliability (indirect effect = 0.497). These results suggest that competence does not generate sustainability benefits automatically. Rather, its operational value is realised when professional capability is translated into practices such as efficient route selection, adaptive speed management, fuel monitoring, energy-efficient navigation, and environmentally responsible voyage decision-making.

The principal theoretical contribution of this study lies in integrating three research domains that have frequently been examined separately: management-level maritime competence, green voyage management, and sustainable vessel performance. The proposed framework positions the Master not only as a navigational and safety authority but also as a strategic actor in the implementation of maritime decarbonisation and operational-efficiency objectives. In this sense, the

technical management challenge in which human competence, technology, and operational practice function as interconnected elements.
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study provides a socio-technical perspective in which sustainable shipping performance emerges from the interaction between human competence, operational management, and technological capability.

From a managerial perspective, the findings indicate that shipping companies should complement investments in voyage-optimisation technologies, fuel-monitoring systems, weather-routing platforms, and energy-efficiency measures with competency development for Masters and deck officers. Training should increasingly incorporate energy-efficient voyage planning, carbon-aware operational decision-making, fuel-performance interpretation, environmental performance management, and the ability to balance efficiency objectives with navigational safety and commercial requirements.

For maritime education and training institutions, the findings support stronger integration of sustainability-oriented competencies into management-level nautical education. Existing competence areas associated with IMO Model Course 7.01, including voyage planning, navigation management, risk assessment, decision-making, and bridge resource management, can be strengthened by incorporating green navigation, energy-conscious voyage execution, and environmental performance considerations. Such integration would help prepare maritime professionals for operational responsibilities under increasingly stringent decarbonisation requirements.

The study also has implications for maritime regulators and shipping-policy stakeholders. Decarbonisation strategies should not be limited to technical standards, alternative fuels, or vessel-efficiency requirements. Competency-based approaches may also contribute to achieving environmental objectives by strengthening the capacity of maritime professionals to implement green operational practices effectively.

Several limitations should be acknowledged. The current framework relies primarily on perceptual construct measurements rather than direct vessel-operational data. Future studies should therefore incorporate objective indicators such as Automatic Identification System records, actual fuel-consumption data, Carbon Intensity Indicator values, voyage duration, speed profiles, weather-routing records, and vessel-performance reports. Such data would allow the relationships identified in this study to be evaluated against observed operational performance.

Future research should also examine whether the proposed relationships differ across vessel types, shipping segments, geographical regions, organisational cultures, and operational environments. Comparative studies involving container ships, bulk carriers, tankers, and passenger vessels could determine whether the strength of the MVPC–GVM–performance relationship varies according to vessel characteristics and commercial operating requirements. Longitudinal research would also be valuable for assessing whether improvements in

competence and Green Voyage Management lead to sustained changes in fuel, emission, and reliability performance over time.

Overall, the study concludes that improving sustainable shipping performance requires more than technological advancement alone. Cleaner fuels, digital systems, and optimisation technologies provide important technical capabilities, but their operational effectiveness depends partly on the competence of maritime professionals who interpret information and make voyage decisions. By demonstrating the role of Green Voyage Management as the mechanism connecting Master's Voyage Planning Competence with Fuel Efficiency, Emission Performance, and Operational Reliability, this study provides a human-centred and operational perspective on the transition toward more efficient, reliable, and environmentally responsible commercial shipping.

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