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# Green Voyage Planning: A Literature Survey on the Role of Sustainable Technologies and Strategies in Maritime Operations

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ABSTRACT: The rapid transition of the maritime sector toward emission-reduction goals set by international regulators leads to increasing pressure on the industry. Within this context, the present study aims to explore the potential impact of green technologies and strategies (GT&S) on voyage planning, a core process governed by IMO provisions, central to ensuring safe and sustainable navigation. The analysis highlighted current research gaps and proposed insights for future studies, with the aim of supporting the ongoing effort toward maritime decarbonization. In order to explore how GT&S may influence voyage planning, a targeted literature survey has been conducted. The selected contributions were grouped into six categories reflecting current technological and operational trends. Then, their potential impact on the components of voyage planning was assessed from a qualitative perspective. The survey suggests that all components are likely to be affected, introducing challenges which have been explored. The fact that most scholarly efforts appear to be primarily directed toward GT&S enabling short and medium-term sustainability reveals future research opportunities that cannot overlook the specificities of the shipping segment examined. The human element, in particular the role of masters and relevant stakeholders, also emerges as pivotal in managing this transition, supporting the need for further research focused on onboard operators.

## 1 INTRODUCTION

The shipping sector has been experiencing increasing pressure to reduce emissions, both of nitrogen and sulfur oxides and greenhouse gases (GHG). To promote sustainability in the maritime industry, Annex VI of the MARPOL convention has progressively introduced several measures and strategies in recent years, such as Emission Control Areas (ECAs), ship energy efficiency management, and requirements concerning the carbon intensity for international shipping. Other factors aimed at boosting the sector's decarbonization are the revised IMO GHG strategy, setting the ambitious target of carbon neutrality for 2050 (IMO, 2023), and the introduction of market-based measures affecting the maritime industry, such as the Emissions Trading System (ETS). Within this complex scenario, ship owners and operators are called to enhance the vessels' sustainability, considering the time constraints often set by the regulations. According to DNV (2023), many strategies may be considered in order to effectively reduce the impact of the ships in terms of emissions. Among these possibilities, those identified as having the greatest potential to ensure the sustainability goals include using alternative routes, reducing the vessels' speed, using alternative fuels, and implementing innovative technologies such as fuel cells or batteries. Notably, the mentioned technologies and strategies can be expected to significantly impact the ship's management, affecting navigation, port operations, and fuel consumption. The latter, in addition to directly having an effect on emissions, significantly influences the financial performance of the shipping company, as fuel expenses account for approximately 47 % of voyage costs, according to Stopford (2008). In other words, the voyages of manned vessels are expected to be affected in various ways by the aforementioned solutions. From the perspective of onboard management, chapter V of SOLAS Convention and section A-VIII/2 of STCW Code establish requirements regarding voyage planning. Among these, the following are deemed relevant to the present work.

IMO regulations emphasize that the intended voyage has to be planned in advance under the Master's responsibility, using adequate, appropriate, and up-to-date information (such as nautical publications and charts as well as the ship's technical data). During this process, the ships' routing systems have expressly been mentioned to be accounted for, as well as the required compliance with the environmental measures. Besides, all navigational hazards consistent over time or foreseeable, as well as weather conditions, have to be considered. The planned track has to guarantee an adequate sea room in order to ensure safe navigation; as a result, a set of margins of safety is often adopted. Once the plan is developed, it has to be continuously available to deck officers in charge of the watch and clearly displayed on the navigational charts. In addition to these provisions, which are primarily related to navigation, IMO regulations set out others that impact ship management from a broader perspective. The required needs for the voyage have to be carefully established by the Chief Engineer in cooperation with the Master. More precisely, an estimation of all consumables is required, including fuel, water, and spare parts. Additionally, the Master's autonomy in decision-making on matters related to safety and environmental protection is safeguarded by the aforementioned regulations. Specifically, it is required that neither owners, operators, nor any other person shall constrain the Master in exercising his professional judgment to make and implement such decisions.

Given their importance, the mentioned requirements are often integrated into onboard procedures established by shipping companies, becoming part of the Safety Management System (SMS). To enhance the effectiveness of this process, the shipowners' association International Chamber of Shipping has issued guidelines (ICS, 2022), which in Chapter 3 outline the key points for developing the SMS section related to the planning of the voyage. The current state of navigation procedures, particularly in the cruise ship industry, often exceeds the regulations' minimum standards, as Di Lieto (2015) indicates. However, this study only focuses on the IMO requirements, allowing for a more comprehensive assessment of the impact of green solutions on the globalized shipping sector.

### 1.1 *Voyage Planning Guidelines*

The SOLAS Convention refers to the Guidelines for Voyage Planning (IMO, 1999) to provide more detailed information for officers and masters. It recommends planning the voyage from departure to arrival berth, including pilotage in harbours or restricted waters. Furthermore, voyage planning is divided into four components, which are briefly outlined below, focusing more on what is considered relevant for the present work.

#### 1.1.1 *Appraisal*

This component involves gathering all available information relevant to the intended voyage plan and aimed at identifying all hazards, safely navigable areas, and zones subjected to environmental restrictions. It involves a large number of items that are difficult to list, some of which are explicitly mentioned in the guidelines. Among them are the vessel's technical conditions and the pertinent certificates, which may lead to operational constraints, as well as manoeuvring or navigation limitations. Besides, an appropriate set of nautical publications has to be included in the appraisal, in particular up-to-date nautical charts, sailing directions, lists of radio aids to navigation, and other relevant sources. Data related to climate and weather conditions have to be gathered during this first step, along with information concerning the availability of weather routing services. Notably, the guidelines recommend consulting sources that provide information on the availability of emergency support arrangements in the ports.

#### 1.1.2 *Planning*

Based on the information gathered during the appraisal, a detailed voyage plan has to be developed and made available both in the relevant log and notebook, as well as on navigational charts. This document is intended to serve as a reliable tool for ensuring safe, environmentally compliant, and efficient navigation. Among the relevant elements that should be included in the plan, the plot of the entire route's features, dangerous areas, environmental protection measures, required speed alterations, and the course alterations design are notable factors. A set of proper safety indicators is recommended at this stage, which includes the evaluation of the safe speed and the estimation of minimal vessel clearances required. Contingency measures for emergencies requiring deviation from the planned route are also to be included, outlining alternative actions, such as moving the vessel to deep water, seeking a port of refuge, or anchoring in a safe area. These measures have to be planned considering the available emergency response services, onboard and shore-based resources, as well as the specificities of the vessel.

#### 1.1.3 *Execution*

The guidelines clearly state that the plan has to be executed. The document in this section once again highlights the significant reliance on the Master's professional judgment. In particular, the Master is responsible for assessing situations where unacceptable hazards to navigation may arise or where enhanced manning for navigational and engine watches may be required during the execution. Notably, this is not considered a "static component" but one that may evolve as circumstances change. By listing key elements, guidelines help to identify the main factors leading to departures from the plan. These include time constraints for reaching critical points (particularly those influenced by tides and tidal flows) or the presence of hazardous areas. Meteorological conditions and weather routing information are included as elements that may contribute to such deviations.

### 1.1.4 *Monitoring*

It is required that the vessel's movement is continuously monitored. This implies, on one hand, that the voyage plan remains readily accessible and easily consultable by the officers in charge. On the other hand, effective monitoring relies on the proper use of navigational systems designed for this purpose. According to IMO (2007), these systems are associated with route monitoring, collision avoidance, and track control tasks, primarily including ECDIS, radar, and track control systems. The guidelines then highlight the strong interconnection between monitoring and execution, as both take place simultaneously. For instance, any modifications to the plan have to be clearly recorded and made readily available to the personnel in charge.

## 1.2 *Further considerations*

As previously mentioned, the four components discussed are grounded in IMO regulations. From a broader perspective, however, it is useful to include two additional preliminary steps prior to the appraisal: voyage instructions and the confirmation of the intended destination. These elements are particularly relevant in certain cargo ship operations, where early-stage decisions can influence the overall voyage planning.

# 2 METHODOLOGY

On the basis of the previous considerations, this study aims to investigate the potential impact of GT&S on voyage planning and suggest possible research gaps as well as future research opportunities. To address this, the two research objectives have been formulated:

RO1: To critically examine the pertinent academic literature related to the impact of green technologies and strategies on voyage planning, focusing on the officers' and onboard management perspective.

RO2: To provide insights into key challenges associated with the adoption of green technologies and strategies for each component of the voyage planning, highlighting potential gaps in the literature and suggesting future research directions to address these challenges.

To achieve RO1, a literature survey has been carried out. According to Klakeel et al. (2023), such an approach, consisting of querying bibliographic databases to detect relevant contributions from the past five years, could be effective in order to do an explorative analysis concerning green technologies in the maritime sector. Given the growing research interest in the decarbonization of the shipping industry and the specific focus of this study, multiple selection criteria have been established for the survey, as outlined in Figure 1 and Table 1. This strategy has been selected as a similar approach was adopted in previous studies (Jovic et al., 2022; Fan et al., 2023), which, despite being more complex than the present work, have addressed a broad research domain concerning the same industry.

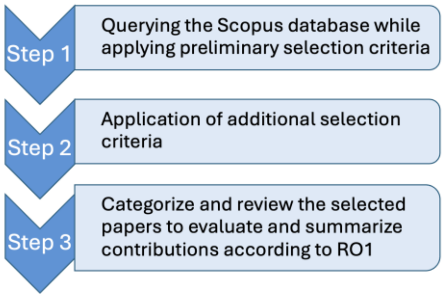



Figure 1. Steps of survey (source: authors' own elaboration).

Table 1. Description of the adopted selection criteria.

| Preliminary selection criteria | |
|---|---|
| Inclusion | Exclusion |
| Title, abstract and keywords in accordance with the search string;<br>Journal papers (articles and reviews);<br>Contributions at final publication stage;<br>Age of publication within 2020 and 2025. | Subject areas excluded: health and nursery science, pharmacology, neuroscience, art and humanities, agricultural and biologicals science, areas related to genetics, biology and biochemistry, chemical engineering and material science.<br>Non-English languages. |
| Additionally selection criteria | |
| Inclusion | Exclusion |
| The research outcomes of the article has the potential to directly or indirectly impact one or more components of the voyage planning or the Master's autonomy in decision-making. | Papers not mainly focused on maritime industry;<br>Contributions addressed only to decision-makers of shipping companies to effectively deploy ships, with a limited or negligible impact on onboard operations.<br>Studies addressed only to autonomous vessels. |

Source: authors' own elaboration

The Scopus database was queried in February 2025 using the string: (vpp OR "voyage passage planning" OR "passage planning" OR "route") AND (ship OR vessel* OR maritime) AND (green OR emission*). Upon completion of step 1, a total of 630 articles have been retrieved from the database. Subsequently, such papers have been screened by applying the additional selection criteria, primarily focusing on their abstracts and overall research outcomes. At the conclusion of step 2, 63 articles were selected for the analysis. According to Shukla (2017), step 3 involved the review of such contributions, intended to summarize and critically evaluate the papers' content in accordance with the aim of this work.

To achieve RO2, the survey findings were critically examined to identify potential challenges that the implementation of GT&S may pose to voyage planning. In this phase, the main outcomes were graphically summarized to provide a comprehensive view. Afterward, potential gaps were suggested to identify future research opportunities.

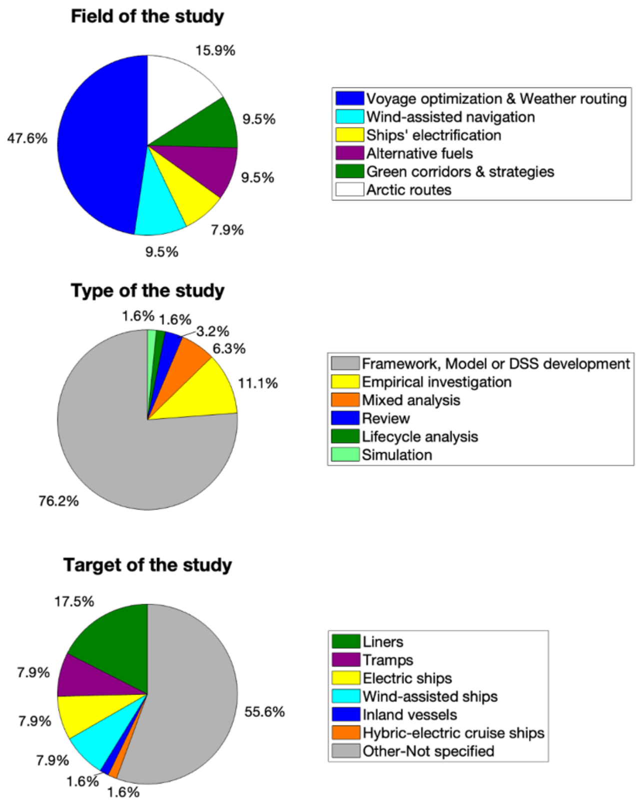
The main limitations of this study lie in its exploratory nature. The topic addressed is extremely broad, and some level of generalization was therefore unavoidable. Moreover, the literature survey was limited to a relatively short time frame, and adopted highly selective criteria (excluding, for instance, conference papers and book chapters). As such, the present work should be regarded only as a preliminary contribution that offers insights to be further validated and deepened in future studies.

## 3 OUTCOMES OF THE SURVEY AND DISCUSSION

### 3.1 *Impacts of GT&S on voyage planning*

To achieve RO1, a literature survey has been carried out, and the main findings are summarized in the Appendix. As outlined in Figure 2, the papers retrieved were primarily categorized according to the research field and nature of the study, and, where specified, the type of vessels they address.

Figure 2. Description of the sample reviewed (source: authors' own elaboration).




Nearly half of the contributions fall under the category of voyage optimization and weather routing (47.6%), highlighting the central research interest in this area, considered a key pathway to decarbonize the sector by the scientific community. Notably, an appreciable share of studies involving technologies and strategies aimed at supporting long-term sustainability have been reported, as well as a concrete interest in evaluating Arctic routes as a valuable measure to reduce the GHG emissions of merchant vessels. Most studies (76.2%) propose the development of frameworks, models, or decision support systems (DSS), demonstrating the prevailing quantitative approach often adopted, aimed at developing effective tools for decision makers and seafarers. Regarding the targeted vessel types, although 55.6% of studies do not specify a particular focus, it can be inferred that they target either all vessels, specific stakeholders, or public administrations. Among the other research, a non-negligible share focuses on liners (17.5 %). This category includes both the studies explicitly focused on liners and those addressing vessels operating on pre-established and regular scheduling routes (Babicz, 2015), such as ferries. On the other hand, 7.9 % of articles deal with GHG reduction of tramp shipping. The remaining part of the papers is related to specific crafts (wind-assisted ships, electric or hybrid vessels) or to inland navigation.

#### 3.1.1 *Voyage optimization & Weather routing*

This research area encompasses measures aimed at reducing various quantities (such as fuel consumption, GHG emissions, costs, and voyage duration) to enhance vessels' environmental compliance and energy efficiency through the selection of appropriate navigation parameters. Most of the identified studies propose single or multi-objective optimization models addressed to decision-makers or onboard officers. These frameworks typically include constraints related to the voyage's first and last waypoints, arrival time window, and operational safety. When the forecasted sea state and weather conditions are also included among the input variables, the literature generally refers to weather routing. The navigation parameters most frequently affected in the reviewed models are speed and legs design, which collectively account for 63.3 % of the cases. Concerning speed adjustment, Zhao et al. (2025), Yang et al. (2024), and Wang et al. (2021) proposed models aimed at providing directly RPMs or engine powers to officers, reducing operational complexity. However, as indicated by Yang et al. (2020), it is not always clear whether voyage optimization systems indicate SOG or STW suggestions, requiring adequate interpretation skills by the users. Interestingly, many studies (such as Li et al., 2024 and Xie et al., 2023) include trim adjustment to enhance energy efficiency. Regarding navigational constraints, various papers expressly refer to areas to be avoided, shallow waters in relation to bathymetry, and obstacles. The frameworks developed in some contributions also account for other factors useful to ensure emissions compliance or effective nautical operations. For instance, Grandcolas (2022), Ma et al., (2021), and Kuhlemann et al., (2020) consider ECAs in their proposed frameworks, acknowledging the higher costs associated with sailing through these zones. The results presented by Grandcolas (2022) also indicate that the developed algorithm is capable of avoiding ECAs in some cases. Cheng et al. (2025) include compliance with CII regulations and the selection of cargo types and quantities in their voyage optimization model addressed to the tramp shipping sector. Models and frameworks have also been reviewed that take into account other relevant factors concerning voyage planning, such as pirate areas (Kuhlemann et al., 2020) or under keel clearance (Mannarini et al., 2024). In the same vein, Nzualo et al. (2021) outline a speed optimization framework mainly based on tides to improve the environmental performance of merchant shipping.

Recent research addresses the current limitations of voyage optimization and weather routing systems. Among the most relevant efforts, the improvement of fuel consumption prediction models is deemed essential (Yang et al., 2024). Another critical aspect is the refinement of the multi-objective approaches

(Grifoll et al., 2022), which are considered paramount (Ma et al., 2024). Within this context, some studies pointed out that assigning different weights to objectives may produce different results (Ma et al., 2021; Zhen et al., 2020), leading to a possible lack of transparency for the onboard users. Cheng et al. (2025) further point out the potential conflict between multiple and complex objectives. Concerning weather routing, the quality of the forecasts is deemed crucial for the systems' performance (Guo et al., 2024). To address this, efforts have been made to enhance the resilience of the models, for instance, by increasing the spatial and temporal resolutions of input data. Adaptive routing approaches are emerging as a necessary feature for long voyages (Mannarini et al., 2024, Xie et al., 2023), allowing dynamic adjustments of the navigation parameters based on real-time weather data.

The mentioned considerations, together with the findings summarized in the Appendix, indicate that voyage optimization and weather routing systems have the potential to influence multiple components of voyage planning. Given that the quality of input data is considered critical, a proper appraisal seems crucial. Moreover, as navigation parameters are often affected, the other components are therefore impacted as well.

#### 3.1.2 *Wind-assisted navigation*

This research area aims to convert the wind's kinematic energy into additional thrust, which supports the vessel's propulsion and reduces fuel consumption and, therefore, GHG emissions. According to Xing et al. (2020), this is possible by implementing onboard technologies such as wing sails, kites, or Flettner rotors. These structures have the potential to impact, either temporarily or permanently, the vessel's structure and reduce the air draught. The adoption of wind-assisted propulsion can also affect navigation. For instance, the results of Mason et al. (2023a) suggest combining voyage optimization with this technology to drastically cut carbon emissions. Similarly, Guzelbulut et al. (2024) indicate that speed adjustment and transit in favourable wind zones can reduce energy consumption. This study also proposes to enable delays to obtain the optimal conditions. Besides, Mason et al. (2023a) and Sun et al. (2022) address weather routing models affecting both speed and way points design to reduce the fuel consumption of wind-assisted ships. These considerations offer insights into how the adoption of wind-assisted technologies may influence the elements of voyage planning, such as speed and route design, ETA-related aspects, and navigational constraints.

#### 3.1.3 *Ships' electrification*

This category includes vessels equipped with electric propulsion and auxiliary systems, which may also incorporate batteries and other energy generation or storage technologies. Commonly referred to as all-electric ships, these vessels represent a key focus of current research, as ships' electrification is considered a promising pathway to achieve sustainability goals (DNV, 2023). As summarized in the Appendix, the reviewed studies suggest that such ships are expected to become more widespread in inland navigation, short-sea shipping, and vessels operating on fixed routes. The surveyed literature indicates that the configuration of onboard systems calls for appropriate energy management and, eventually, charging strategies. To address these challenges, optimization models are proposed to decision-makers and officers, often sharing the goal of reducing total or operational transport service costs. Focusing on the impact on the voyage planning, Havre et al. (2024) propose a system for designing high-speed battery electric passenger craft networks that incorporate dynamic scheduling based on transport demand, with implications for both route selection and speeds. Hein et al. (2021) present an optimization model for electric vessels fitted with hybrid energy storage systems, which, taking into account the degradation of the energy stored, the sea-state conditions, and obstacles, is capable of solving problems related to routing and speed optimization. Furthermore, Gao et al. (2024) advocate for a joint evaluation of voyage optimization and power generation in the context of electric ships. Their study proposes a multi-objective optimization model designed to minimize both operational costs and $SO_2$ emissions, influencing route and speed planning, while also accounting for ECAs.

#### 3.1.4 *Alternative fuels*

The adoption of alternative fuels such as natural gas, methanol, hydrogen, and ammonia is considered a promising decarbonization strategy for shipping. In this perspective, maritime transport is facing challenges that, among the most relevant, concern the lack of adequate international regulations, the establishment of reliable supply chains, and safety-related issues, leading to the potential reshaping of transport services, with possible implications on voyage planning. The contributions examined pointed out challenges concerning the availability and adequacy of bunkering infrastructures for merchant shipping, confirming the reviews of Xing et al. (2020). More in detail, some authors recall the limited availability of LNG and methanol bunkering in ports (He et al., 2024; Gao et al., 2025) while the situation appears even more critical with regard to fuels enabling zero emissions, such as green hydrogen (Atilhan et al., 2021). The low volumetric energy density of alternative fuels, especially those allowing net-zero goals (Law et al., 2021), may lead to carrying onboard a limited quantity of energy, with the subsequent necessity to increase the frequency of bunkering. Within this context, He et al. (2024) and Gao et al. (2025) suggest voyage optimization systems addressed to tramps and liners, respectively. It is worth noting that both frameworks are designed to minimize costs, considering fuel prices and suggesting adequate bunkering strategies. In doing so, the first model affects the choice of port of calls and speed, while the second provides the recommended speed for the voyage. The complexity of handling alternative fuels, coupled with their chemical properties, represents another critical factor that often leads to hazards for nautical operations (Gao et al., 2025; Atilhan et al., 2021).

The mentioned findings depict a complex scenario in which onboard operators and managers are required to collaborate. It has also been outlined that certain navigation parameters may be affected in order to ensure profitability, especially in a context where fuel costs are expected to remain high in the medium term.

### 3.1.5 *Green corridors & strategies*

Green Shipping Corridors (GSCs) represent a strategy considered highly promising for achieving maritime industry decarbonization. According to DNV (2023), these corridors encompass maritime routes connecting some ports, specifically characterized by zero-emissions maritime operations. This concept aims at developing the necessary infrastructure and frameworks to support the adoption of alternative fuels, zero-emission technologies, and other relevant measures. The active collaboration among shipowners, stakeholders, and administrations is considered essential, given the complexity involved in developing GSCs. Several challenges, mainly related to appraisal and planning, emerge from the literature analysed concerning this strategy. For instance, Jesus et al. (2024) highlight, in their introductory remarks, critical factors such as fuel availability and the existing regulatory gaps. On the other hand, Bengue et al. (2024) indicate the necessity of infrastructure investments alongside the implementation of suitable safety and security measures concerning the realization of GSCs.

Other strategies and measures potentially affecting voyage planning have emerged from the literature. Among these, slow steaming, defined as operating vessels at speeds lower than their design speed, has been recognized as an effective approach (Gospić et al., 2022). Notably, Xing et al. (2020) indicate the human factor as an operational measure to cut emissions, emphasizing the potential for emissions reduction through improved education and training of ship operators in energy-efficient practices. Furthermore, both Xing et al. (2020) and Poulsen et al. (2020) address, albeit differently, the environmental impact mitigation achievable through the optimization of port operations, such as by reducing ships' turnaround time. Finally, Hwang et al. (2023) propose the emission control route concept, aimed at overcoming the limitations of ECAs and speed reduction programs, focusing their analysis on liner shipping operations.

### 3.1.6 *Arctic routes*

A non-negligible share of the papers reviewed focus on Arctic routes (15.9 %), which are gaining increasing attention due to the distance savings they offer along several commercial routes. The scientific community is called upon to assess the balance between the reduction of GHG emissions achieved through shorter sailing distances and the environmental impact on the Arctic ecosystem, often taking into account fuel price fluctuations, operational costs, and additional safety concerns. The studies reviewed indicate a plausible increase in traffic along Arctic routes expected in the coming decades due to more favourable ice conditions (Chen et al., 2022; Christensen et al., 2022). This upward trend appears to be confirmed by Tsai et al. (2023), who also consider compliance with CII regulations. Ding et al. (2020) indicate that the Northern Sea Route (NSR) would remain more advantageous than the Suez Canal Route under various carbon tax scenarios applied to the liner shipping, further suggesting a potential increase in traffic. Notwithstanding the possible economic and environmental advantages of sailing on arctic routes, some papers also consider operational risks. Christensen et al. (2022) advocate for the adoption of additional measures focused on the search and rescue (SAR) capabilities and environmental protection. Specifically, they recommend that authorities prioritize the development of adequate infrastructure in proximity to high-risk areas while encouraging shipping companies to invest in reinforced vessels, characterized by appropriate polar class certification. Chen S. et al. (2022) also examine navigational hazards, indicating sea ice as the primary impediment to navigation along the NSR, which causes significant risks even to structurally robust vessels during the winter season. Researchers propose models to support navigation as well. For instance, Chen A. et al. (2023) present a multi-objective optimization algorithm for path planning in Arctic waters to minimize navigational risks connected to ice and operational costs. Ryan et al. (2021) developed a ship performance model, which the authors present as a tool to support Arctic navigation, primarily aimed at predicting fuel consumption while also accounting for ice conditions.

The reviewed literature highlights that Arctic routes may affect voyage planning in several ways. First, the region's specificities increase navigational hazards in a sea area lacking adequate infrastructure. Additionally, optimization systems targeting officers and decision makers are suggested, which are likely to influence onboard operations related to navigation.

## 3.2 *Challenges and research gaps concerning voyage planning*

The information obtained from the survey, discussed in Section 3 and summarized in the Appendix, also contributed to the achievement of RO2. In particular, the survey suggested that the implementation of GT&S may pose challenges affecting the four components of voyage planning, as summarized in Figures 3 and 4.

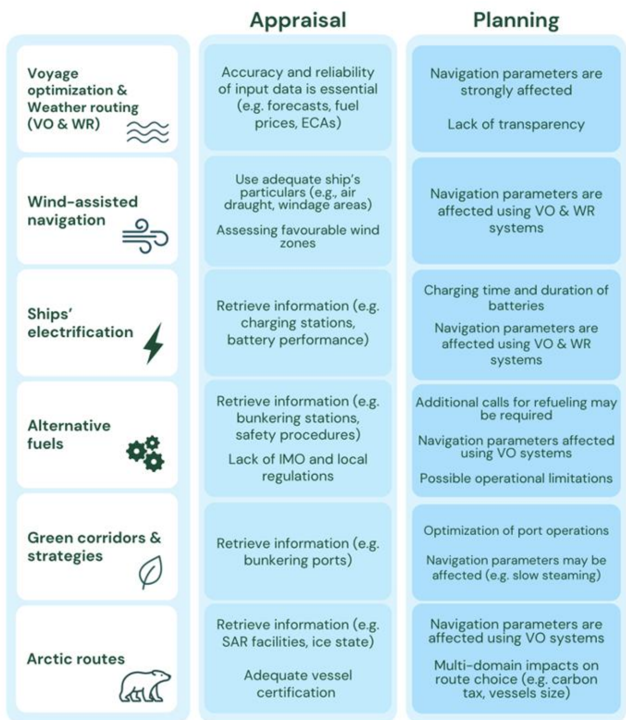



Figure 3. Potential challenges related to the adoption of GT&S impacting appraisal and planning (source: authors' own elaboration).

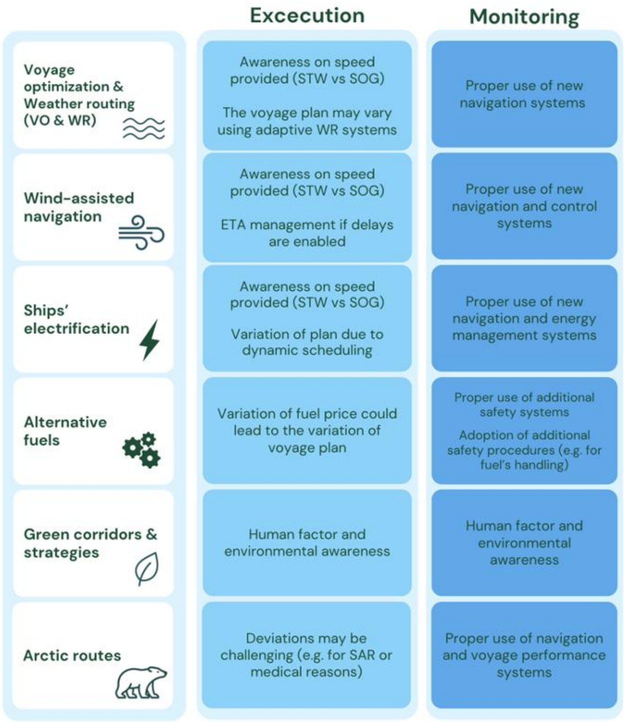



Figure 4. Potential challenges related to the adoption of GT&S impacting execution and monitoring (source: authors' own elaboration).

One of the key challenges identified concerns potential issues in retrieving information during the appraisal phase. For instance, the reviewed literature emphasizes the importance of reliable weather and sea-state forecasts as valuable input data for weather routing, along with other essential inputs for voyage optimization models (such as fuel prices, ECAs, and areas to be avoided). Furthermore, with respect to alternative fuels and green corridors, the lack of bunkering infrastructure, ongoing safety concerns, and the lack of regulations suggest that, at present or in the short to medium term, accessing adequate information through official sources may be challenging. Another potential criticality lies in the increased amount of information that officers will be required to collect during the appraisal phase. In addition to those already mentioned, particular attention should be paid to data related to the characteristics of green technologies and their associated certifications.

The voyage, both in its planning and execution, may also be influenced by bunkering or charging strategies required to address the low volumetric energy density associated with green storage systems, leading to other potential concerns.

The adoption of GT&S is also expected to increase the technological complexity of vessels and navigation systems. In light of ongoing research trends, the use of more advanced optimization models and decision support systems appears necessary. While this evolution offers potential benefits, it also introduces challenges as seafarers will be required to have adequate skills and awareness in operating such systems, particularly in view of the potential lack of transparency outlined in the literature. Furthermore, this shift will demand closer collaboration between masters and decision-makers within shipping companies, as many of the proposed models are explicitly designed to reduce costs and rely on economic input data. This latter aspect may, in turn, create issues or constraints on the exercise of the master's professional judgment, thereby limiting the potential benefits of adopting GT&S. Similarly, the arising of safety-related issues (such as those associated with alternative fuels or the increased risks in navigation) may generate tensions between the company and the Master, as well as impact onboard operations, thereby confirming that the human factor should also be carefully considered in this transition.

It should also be noted that, according to Figure 2, the majority of the reviewed studies address measures which, in line to DNV (2023), are not sufficient on their own to achieve the net-zero target, such as weather routing, voyage optimization, and polar routes (accounting for 63.5% of the sample). Moreover, these areas are already regulated by mandatory IMO instruments: weather routing is explicitly mentioned in IMO (1999), while polar navigation falls under SOLAS Chapter XIV requirements and the Polar Code. By contrast, other topics with greater potential to enhance sustainability appear to be underexplored in terms of their implications for voyage planning.

On the basis of the previous considerations, several opportunities for future research can be identified. First, the reviewed sample reveals a scarcity of studies directly addressing seafarers and adopting qualitative research approaches, highlighting the need to further investigate the impact of GT&S in voyage planning by involving the perspective of masters and deck officers. The findings also suggest the importance of engaging other relevant stakeholders in future investigations, such as harbour pilots regarding safety issues, and hydrographic offices concerning the availability of information in nautical publications. The impact of low or zero-emission technologies, such as those related to the adoption of alternative fuels, on voyage planning emerges as a further potential area of investigation. Finally, given that several studies are specifically focused on liners or tramps and considering the significant differences between these shipping segments, it appears necessary to carry out future studies for these vessel types separately.

## 4 CONCLUSIONS

The findings of the survey indicate that all components of voyage planning are expected to be affected by the adoption of GT&S. In order to meet the ambitious sustainability goals set by international regulations, an increased complexity of onboard systems is expected, leading to the potential challenges outlined in the present study. This scenario is further complicated by the possible rise in risks associated with maritime transport, for instance, regarding the utilization of alternative fuels or during polar navigation. Given the identified research gaps, future investigations should involve the seafarers' perspective more directly. In particular, exploring the viewpoint of masters appears essential, as they represent a critical link between onboard operations and shore-based decision makers. It seems further necessary to differentiate future analyses between liner and tramp shipping segments, due to their operational and structural differences.

APPENDIX

Table 2. Key features of the sub-sample focused on voyage optimization and weather routing. All studies address models, frameworks, or DSS.

| Reference of paper | Navigation parameters affected | Meteo-oceanographic elements considered | Quantity optimized | Notes |
|---|---|---|---|---|
| Zhao et al., (2025) | Engine RPM, legs design | Wind, Waves | Voyage duration, $CO_2$ emissions | Elements considered: Shallow waters avoidance |
| Cheng et al., (2025) | Speed, legs design | | Total costs | Addressed to Tramps. Elements considered: Fuel price, cargo selection and quantity, CII compliance |
| Song et al., (2025) | Engine power, legs design, ROT | Wind, Waves, Currents | Fuel consumption, $SO_2$ emissions | |
| Guo et al., (2024) | Speed, legs design | Wind, Waves | Fuel consumption, voyage duration | |
| Yang et al., (2024) | Engine RPM | Wind, Waves | Fuel consumption | |
| Li et al., (2024) | Speed, legs design, trim | Wind, Waves | Fuel consumption | |
| Mannarini et al., (2024) | Legs design | Wind, Waves, Currents | $CO_2$ emissions | Elements considered: UKC |
| Ma et al., 2024 | Speed, legs design | Wind, Waves | $CO_2$ emissions, voyage duration, operational costs | Elements considered: shallow waters, obstacles |
| Zhao et al., (2024) | Speed, legs design | Wind, Waves | Fuel consumption, voyage duration | Elements considered: shallow waters |
| Xie et al., (2023) | Speed | | Fuel consumption | |
| Wang H. et al., (2023) | Speed | | Total costs | Addressed to inland vessels. Elements considered: fuel price considered, Time window and width of narrow channels |
| Wang Z. et al., (2023) | Speed | Wind, Waves, Drifting ices | Fuel consumption | Addressed to Hybric-electric cruise ships. |
| Du et al., (2023) | Speed, legs design | Wind, Waves | Fuel consumption | Elements considered: areas to be avoided |
| Zhou et al., (2023) | Speed, legs design | Wind, Waves | One customizable quantity (i.e Fuel consumption, voyage duration, etc.) | |
| Grifoll et al., (2022) | Speed, legs design | Waves | Voyage duration | |
| Grandcolas (2022) | Speed, legs design | Wind, Waves | One customizable quantity (i.e Fuel consumption, voyage duration, etc.) | Elements considered: ECAs, area to be avoided |
| Borén et al., (2022) | Speed, legs design | Waves | Voyage duration | |
| Li et al., (2022) | Speed | Wind, Waves, Currents | Fuel consumption | Addressed to Liners |
| Gao et al., (2022) | Trim | Wind | Energy consumption | Addressed to Liners |
| Ma et al., (2021) | Speed, legs design | Wind, Waves | Fuel consumption, Total costs | Addressed to Tramps. Elements considered: ECAs |
| Wang K. et al., (2021) | Speed, legs design | Wind, Waves | Energy consumption | |
| Nzualo et al., (2021) | Speed | Tides | Operational costs | Addressed to Tramps. Elements considered: shallow waters |
| Wang H. et al., (2021) | Engine power, legs design | Wind, Waves | Fuel consumption, arrival punctuality | Elements considered: shallow waters |
| Zhao et al., (2021) | Speed, legs design | Wind, Waves | Fuel consumption, voyage duration, meteorological risk | |
| Johannessen et al., (2021) | | Detailed oceanographic data | | |
| Kuhlemann et al., (2020) | Speed, legs design | Wind, Waves | Fuel consumption | Elements considered: ECAs, pirate zones |
| Wang K. et al., (2020) | Speed, legs design | Wind, Waves | Fuel consumption | |
| Yang et al., (2020) | Speed | Currents | Fuel consumption | |
| Li et al., (2020) | Speed | Wind, Waves | Fuel consumption, Operational costs | Addressed to Liners. |
| Zhen et al., (2020) | Speed, legs design | | Fuel consumption, $SO_2$ emissions | Addressed to Liners. Fuel price considered. |

Source: authors' own elaboration

Table 3. Key features of the sub-sample focused on Wind-assisted navigation.

| Reference of paper | Type of the study | If the study involves an optimization model | | | Notes |
|---|---|---|---|---|---|
| | | Navigation parameters affected | Meteo-oceanographic elements considered | Quantity optimized | |
| Ghorbani et al., (2024) | Simulation | | | | |
| Guzelbulut et al., (2024) | Framework, Model or DSS development | Speed, legs design | Wind | Energy consumption | |
| Mason et al., (2023a) | Empirical investigation | Speed, legs design | Wind, Waves | Fuel consumption | The optimization model is used to carry out a simulation |
| Mason et al., (2023b) | Framework, Model or DSS development | | | | Model presented for the calculation of the fuel consumption |
| Sun et al., (2022) | Framework, Model or DSS development | Speed, legs design | Wind, waves | Fuel consumption | |
| Tilling et al., (2020) | Framework, Model or DSS development | Speed | | | Addressed to wind-assisted liners |

Source: authors' own elaboration

Table 4. Key features of the sub-sample focused on the Ships' electrification.

| Reference of paper | Type of the study | If the study involves an optimization model: Navigation parameters affected | Meteo-oceanographic elements considered | Quantity optimized | Notes |
|---|---|---|---|---|---|
| Havre et al., (2024) | Framework, Model or DSS development | Speed, legs design | | Total costs | The study is applied to inland navigation |
| Gao et al., (2024) | Framework, Model or DSS development | Speed, legs design | | Operational costs, $SO_2$ emissions | The study is applied to a container domestic shipping route. ECAs are considered |
| Karountzos et al., (2023) | Framework, Model or DSS development | | | | Addressed to a coastal shipping network |
| Wang et al., (2022) | Framework, Model or DSS development | | | Total costs | Addressed to specific inland areas. Focused on the deployment of all electric ships |
| Hein et al., (2021) | Framework, Model or DSS development | Speed, legs design | Waves | Operational costs, Energy storage degradation | Addressed to ships equipped with hybrid energy storage system |

Source: authors' own elaboration

Table 5. Key features of the sub-sample focused on the Alternative fuels.

| Reference of paper | Type of the study | Fuel | If the study involves an optimization model: Navigation parameters affected | Quantity optimized | Notes |
|---|---|---|---|---|---|
| Gao et al., (2025) | Framework, Model or DSS development | Methanol | Speed | Operational costs | Addressed to Liners. Elements considered: fuel price, ECAs, bunkering ports |
| He et al., (2024) | Framework, Model or DSS development | LNG | Speed, legs design | Total costs | Addressed to Tramps. Elements considered: fuel price, bunkering ports |
| Perna et al., (2023) | Framework, Model or DSS development | Green Hydrogen | | | The study addresses the green hydrogen supply chain |
| Law et al., (2021) | Lifecycle analysis | Main alternative fuel pathways | | | Comparison of alternative fuels from LC perspective |
| Atilhan et al., (2021) | Review | Green Hydrogen | | | The study addresses the green hydrogen supply chain |
| Pfeifer et al., (2021) | Framework, Model or DSS development | Hydrogen | Engine power | | Addressed to Liners |

Source: authors' own elaboration

Table 6. Key features of the sub-sample focused on the Green corridors and strategies.

| Reference of paper | Type of the study | Strategy | Navigation parameters affected | Notes |
|---|---|---|---|---|
| Jesus et al., (2024) | Framework, Model or DSS development | Green shipping corridors | | Mainly addressed to onshore stakeholders |
| Bengue et al., (2024) | Empirical investigation | Green shipping corridors | | Addressed to Liners |
| Hwang et al., (2023) | Framework, Model or DSS development | Emission control routes | Speed, legs design | Addressed to Liners. ECAs are considered |
| Gospić et al., (2022) | Empirical investigation | Slow steaming | Speed | Addressed to Tramps |
| Poulsen et al., (2020) | Mixed analysis | Port call optimization | | |
| Xing et al., (2020) | Review | $CO_2$ emissions reduction in shipping | | |

Source: authors' own elaboration

Table 7. Key features of the sub-sample focused on the Arctic routes.

| Reference of paper | Type of the study | Notes |
|---|---|---|
| Kavirathna et al., (2023) | Framework, Model or DSS development | An optimization model is proposed, aimed at minimizing $CO_2$ emissions or total costs. Speed is the only parameter affected |
| Chen A. et al., (2023) | Framework, Model or DSS development | An optimization model is proposed, aimed at minimizing operational costs. The system supports path planning considering meteorological risks |
| Tsai et al., (2023) | Empirical investigation | Investigate the effect of CII on Arctic routes |
| Li et al., (2023) | Empirical investigation | Feasibility of Arctic sea roads |
| Chen S. et al., (2022) | Empirical investigation | Study regarding the navigability of the Northern sea route |
| Christensen et al., (2022) | Empirical investigation | Risk-based analysis for the Arctic navigation |
| Ryan et al., (2021) | Framework, Model or DSS development | A tool for calculate fuel consumption during Arctic navigation environmental conditions is proposed |
| Dai et al., (2021) | Mixed analysis | Analysis concerning transportation of LNG via Arctic routes |
| Wang Z. et al., (2021) | Mixed analysis | Addressed to Liners networks |
| Ding et al., (2020) | Mixed analysis | Addressed to Liners networks |

Source: authors' own elaboration

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