Research in Transportation Business & Management 59 (2025) 101288

Contents lists available at ScienceDirect

Research in Transportation Business & Management

journal homepage: www.elsevier.com/locate/rtbm

Multi-criteria feature selection on maritime emission abatement alternatives

Kaiqi Xu[a,*], Mario P. Brito[a], Patrick Beullens[b]

[a] Southampton Business School, University of Southampton, Southampton, SO17 1BJ, United Kingdom
[b] Southampton Business School and Mathematical Sciences, University of Southampton, Southampton, SO17 1BJ, United Kingdom

ARTICLE INFO

Keywords:
Analytic hierarchy process
Multi-criteria decision making
Emission reduction
Technology selection
Sustainability port

ABSTRACT

To comply with MARPOL Annex VI, stakeholders face multi-criteria decision-making in technology selection. This study provides an Analytic Hierarchy Process (AHP)-based method to support stakeholders in selecting emission abatement technology aligned with their business demands, taking into account a range of sustainability criteria. The analysis reveals that there is no one-size-fits-all solution to technology selection. Low-sulfur fuel oil and LNG are preferable alternative fuels for large-size commercial (long-sea shipping) vessels due to their better capacity storage savings, while a dual-fuel engine offers flexibility in fuel changeover. Electrification offers zero-emission performance, lower noise levels, and peak energy solutions benefiting cruise ships and short-distance or harbor boats, but tugboats need greener diesel to meet performance criteria. From a policy perspective, our model provides insights into the effects of green transition processes in Norway and Singapore on stakeholders' decisions with respect to port infrastructure and land transport at the portside.

1. Introduction and background

To advance the sustainability of the maritime transport system, the International Maritime Organization (IMO) introduced a series of regulations under the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2020). Annex VI of MARPOL establishes a framework for controlling emissions of nitrogen oxides (NOx) and sulfur oxides (SOx) across global sea areas and Emission Control Areas (ECAs), including EU territories (Bouman et al., 2017; Zis & Cullinane, 2020). In addition to compliance with MARPOL Annex VI, several nations and regions have demonstrated a willingness to implement complementary regulations (Lindstad & Bø, 2018; Lindstad & Eskeland, 2016).

The IMO has proposed a range of operational and technical measures to enhance energy efficiency in shipping. Key operational measures for existing ships include the Energy Efficiency Existing Ship Index (EEXI), the annual operational Carbon Intensity Indicator (CII), and the associated CII ratings (IMO, 2023). For newly designed ships, the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI) serve as primary measures (IMO, 2013). Regarding technical measures, Lloyd's Register (2012) highlights that the primary compliance strategy involves reducing SOx and NOx emissions at their source through methods such as using low-sulfur fuel, while secondary strategies involve treating exhaust gases post-combustion. Examples include the use of scrubbers for SOx reduction and selective catalytic reduction for NOx mitigation. Furthermore, market-based measures, such as the European Emissions Trading System (EU-ETS) and the Quebec Emissions Trading System (QC-ETS), have been proposed to encourage cross-regional integration of maritime emission management (Peng et al., 2023).

Technology selection for the sea transport system is often capital intensive and may lead to irreversible change or a lock-in into a technology that might lose support in the longer term. Although the IMO2020 regulations set stringent thresholds with the coming timeline, the details of practical guidance are still unclear towards SOx and NOx limits (IMO, 2020). Because of the rate of change and the numerous possible alternatives are not yet leading to an established pathway to follow, many shipping companies are still uncertain about what route to take.

1.1. Importance of stakeholder preference elicitation

Intangible socio-cultural perceptions and preferences of stakeholders play a critical role in shaping sustainable transition pathways within the

* Corresponding author.
E-mail addresses: kx3u19@soton.ac.uk (K. Xu), m.p.brito@soton.ac.uk (M.P. Brito), P.Beullens@soton.ac.uk (P. Beullens).

https://doi.org/10.1016/j.rtbm.2025.101288
Received 7 February 2024; Received in revised form 18 November 2024; Accepted 7 January 2025
Available online 13 January 2025

maritime industry (Doukas & Nikas, 2020; Hansson et al., 2019; Li et al., 2020; Voinov & Bousquet, 2010). Emission abatement technologies often have far-reaching implications for the environment, public health, and economic development. By capturing stakeholder preferences, decision-makers can develop solutions that address the social, environmental, and economic dimensions of sustainability.

The adoption of emission abatement technologies, however, can give rise to conflicts due to diverging priorities or perceptions of costs and benefits. Eliciting stakeholder preferences early in the process allows potential disagreements to be identified and addressed proactively, thereby minimizing the risk of delays or project failures (Bjerkan & Ryghaug, 2021).

Emission abatement technologies often necessitate trade-offs between cost, performance, and environmental impact. Stakeholder preference elicitation aids in identifying acceptable trade-offs across diverse groups, guiding the selection of technologies that optimize overall satisfaction, see e.g. De Brucker et al. (2013). Effective stakeholder management is also essential in port governance to balance competing interests, ensure sustainability, and foster economic growth. As highlighted by Lam et al. (2013), it serves as a strategic tool to build consensus, resolve conflicts, and promote the long-term success of port operations.

In our view, the realization of sustainable emission reduction goals requires that enforceable, environmentally friendly measures naturally evolve into publicly accepted and supported behaviors. Only through such alignment between regulation and societal acceptance can long-term sustainability in the maritime sector be achieved.

1.2. Literature review and gap analysis

The evaluation and selection of technology is a process intrinsically connected to various business operations and is shaped by the broader technological, organizational, and business environment (Shehabuddeen et al., 2006). Therefore, in assessing emission abatement technologies and strategies, it is essential to consider a comprehensive range of factors, including technology attributes, available alternatives, environmental regulations, and economic development.

A variety of approaches and methodologies have been developed for technology assessment. Broadly, business-oriented and non-governmental technology assessments tend to address these issues from an economic or technical perspective, whereas public technology assessments often emphasize social considerations, see Tran and Daim (2008).

Pioneering research by Arrow and Raynaud (1986) highlighted the clear and significant relationship between multi-criteria decision theory and social choice. The interplay between these fields has evolved in two primary directions: (1) multi-criteria decision theory provides a robust framework for applied social and public choice, and (2) social choice theory offers valuable theoretical insights to ensure axiomatic consistency in multi-criteria aggregation conventions.

Over the past five decades, decision analysis methods—particularly multi-criteria decision analysis (MCDA) techniques, have emerged as the predominant tools for technology assessment, as evidenced in the comprehensive review by Parolin et al. (2024).

Table 1 provides a summary of the strengths and weaknesses of major MCDA methods.

The Analytic Hierarchy Process (AHP) has been widely applied in technology assessment (Gerdsri & Kocaoglu, 2007; Mandić, Boljat, et al., 2021; Shen et al., 2010; Vargas, 1990), with its earliest documented use in technological choice by Ramanujam and Saaty (1981). Compared to other MCDA methods-such as ANP, TOPSIS, VIKOR, ELECTRE, PROMETHEE, and MAUT, AHP offers a systematic framework that decomposes complex decisions into a hierarchy of objectives, criteria, sub-criteria, and alternatives. This hierarchical design enables decision-makers to evaluate individual criteria independently, offering a transparent and interpretable decision-making process. Through pairwise comparisons, AHP facilitates the assessment of relative preferences between criteria or alternatives, aligning closely with natural human judgment.

Table 1
Strengths and weaknesses of major MCDA methods.

Method	Strengths	Weaknesses
AHP (Analytic hierarchy process)	• Structured hierarchy makes complex decisions easier to analyze. • Pairwise comparisons are intuitive for qualitative and quantitative data. • Consistency check improves judgment reliability. • Allows for sensitivity analysis. • Easy to use and transparent.	• Can become complex with many criteria/ alternatives. • Pairwise comparisons can be time-consuming. • Requires subjective judgments which may introduce bias
ANP (Analytic network process)	• Builds on AHP with more detailed networks. • Considers interdependencies between criteria, useful for complex systems • Provides flexibility in modeling relationships.	• More complex and time-consuming than AHP. • Difficult for non-experts to understand. • Inconsistent results if dependencies are inaccurately represented.
TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	• Focuses on finding an ideal solution, intuitive for ranking alternatives. • Suitable for a wide range of criteria types. • Simple calculations and easy to use.	• Requires data normalization, which can affect results. • Lacks consistency check for subjective judgments. • Less suited for hierarchical structures.
VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje)	• Focuses on achieving a compromise solution close to the ideal and anti-ideal solutions. • Handles interdependence among criteria • Suitable for complex, interrelated decision problems	• Sensitive to the initial selection of weights. • Complex calculations for large datasets. • No hierarchy or consistency check
ELECTRE (Elimination and Choice Translating Reality)	• Useful for screening and ranking based on "outranking" relationships. • Can handle inconsistent data and incomplete information. • Suitable for conflict resolution.	• Complex and challenging to implement for large datasets. • Requires careful tuning of thresholds. • Less transparent, harder to interpret by non-experts.
PROMETHEE(Preference Ranking Organization Method for Enrichment Evaluation)	• Good for ranking and comparing multiple alternatives. • Supports outranking, useful for qualitative data. • Can handle large datasets.	• Lacks hierarchy, making it less intuitive for multi-level criteria. • Sensitivity analysis is limited. • Requires parameter tuning, which can be complex.
MAUT (Multiattribute utility theory)	• Provides a utility score for decision-making • Suitable for decision problems with measurable outcomes	• Requires precise data and utility functions. • Not suitable for problems with qualitative criteria

In the maritime industry, AHP and its variants have been extensively used for sustainability evaluations, as summarized in Table 2. A substantial body of AHP-related literature focuses on assessing alternative fuels or ship technologies (Mandić, Boljat, et al., 2021; Mandić, Ukić

Table 2
Comparative analysis of AHP and its variants for sustainable ranking models (in maritime applications).

References	AHP typology	Problem	Sustainable criteria	Dominant testing/ ordering
Mandić, Boljat, et al., 2021, Mandić, Ukić Boljat, et al. (2021)	AHP	Alternative fuels assessment	Environmental, economic, technological	Simple Additive Weighting
Inal and Deniz (2020)	AHP	Fuel cell assessment	Environmental, economic	–
Wan et al. (2019)	AHP	The development level of LNG fuel ships evaluation	Political, economic, social and technological	SWOT analysis, Evidence reasoning approach, Sensitivity analysis
Asgari et al. (2015)	AHP	Port performance assessment	Economic, environmental, social	Sensitivity analysis
Tseng and Pilcher (2019)	Fuzzy AHP	Port performance assessment	Environmental, economic, technological, human	Evidential reasoning approach
Ren and Lützen (2017), Ren and Lützen (2015)	Fuzzy AHP	Technology selection	Environmental, economic, technological, social-political	VIKOR, Sensitivity analysis
This paper	AHP	Technology selection	Environment, economic, technological, socio-political	Feature model, Perspective-based scenario analysis

Boljat, et al., 2021; Ren & Lützen, 2015; Ren & Lützen, 2017; Wan et al., 2019). However, few studies incorporate critical ship-specific characteristics—such as ship type, size, lifetime, cargo capacity, and voyage distance—into the evaluation framework. This omission potentially creates a gap between theoretical models and their practical applicability. Moreover, limited attention has been directed towards technology evaluation for port infrastructure and land transport systems at the portside.

A notable limitation of the existing MCDA literature is the predominant focus on decision modeling techniques, with comparatively little emphasis on the initial problem structuring phase, see e.g., Slotte and Hämäläinen (2015). Understanding the structure of a decision is crucial, as the foundational principles of certain MCDA methodologies may not align with the expectations or values of decision-makers, see as French (2023). Similar challenges were observed during our application of the AHP method, as discussed in Section 4.1.

An equally critical consideration in MCDA problems pertains to stakeholder involvement. Existing decision-support systems for selecting emission abatement solutions often emphasize consulting shipowners (Mäkitie et al., 2022; Zhang et al., 2021), ship operators (Li et al., 2020; Schinas & Stefanakos, 2014) and port operators (Yu et al., 2019). However, relatively few studies integrate diverse stakeholder perspectives (Doukas & Nikas, 2020; Wan et al., 2019). This lack of inclusivity underscores the need for more comprehensive stakeholder engagement in decision-making processes.

To address these gaps, this paper proposes a novel process for structuring complex problems and modeling decisions. Specifically, it introduces an enhanced AHP-based methodology that enables stakeholders to evaluate and select alternatives in alignment with their unique requirements and strategic objectives. Distinct from Saaty's traditional AHP, the innovation of this approach lies in its integration of problem structuring with decision modeling through the use of a feature model for alternative screening. A comprehensive overview of this AHP-based approach is provided in Section 3.

This paper aims to answer the following questions:

1. What technologies are available for emission abatement in the maritime transport sector?
2. How can an AHP-based approach assist in structuring complex problems and facilitating group decision-making?
3. How can the AHP-based approach support the evaluation and selection of technologies when considering a large number of alternatives and criteria?

The primary contribution of this research is the development of a bottom-up decision-support framework for evaluating emission abatement technologies in scenarios with limited historical data. A feature model for various maritime transport vehicles is designed and assessed based on stakeholders' perspectives.

The rest of the paper is structured as follows: Section 2 reviews emission abatement alternatives in the maritime industry. Section 3 explains the research methodology in detail, and the research protocol is presented. Section 4 presents the data collection method and the proposed methodology. The conclusions and limitations of this research are drawn in Section 6, followed by future direction.

2. Emission abatement technologies in the sea transport system

Sea transport, ports, and land transport at the portside play a major part in the sea transport system (Stopford, 2010). Three dominant approaches have been extensively discussed to reduce emissions in the sea transport system: technological, operational, and market-based approaches (Alamoush et al., 2022). This subsection primarily focuses on reviewing alternative fuels in shipping (Section 2.1), ports and land transport at the portside (Section 2.2).

Norway and Singapore have leadership and competitiveness in both ship ownership and marine technology (Hoong, 2013; Tenold, 2019). The projects made by Norway and Singapore significantly contribute to the wider adoption of IMO's emission reduction strategy. This is reflected in the performances of the government and the Shipowners' Association, whose greenhouse gas (GHG) emission reduction targets go beyond the IMO (Alamoush et al., 2020; Mäkitie et al., 2022). Accordingly, we review the competitiveness of the two countries in the literature. Their strengths and weaknesses are summarized and discussed in the Section 2.3.

In Section 2.4, we review the sustainable criteria in the sea transport system.

2.1. Emission abatement technologies in shipping

2.1.1. Scrubber

Scrubbers are classified as following three types: closed-loop, open-loop, and hybrid (Lloyd's Register, 2012). Among the three modes, open loop systems are relatively cheaper and smaller in size, but their use may be limited by low water alkalinity or local legislation (Brynolf et al., 2014). Although there is an expanding ban on open-loop scrubbers within ECAs, open-loop scrubbers are still an attractive option at this moment, which are predominately preferred by shipping companies with a large distance ratio of shipping services within high seas (Zhao, Fan, et al., 2021., Zhao, Wei, et al., 2021). The closed-loop scrubber, while it can be used anywhere, has a higher operating cost. A hybrid scrubber is a combination of the former two modes and enables the ship to transfer in different modes in different sea areas, but its investment cost is 50 % higher than for an open-loop scrubber (Lindstad et al., 2017).

Overall, the scrubber provides flexibility in operations by switching from high-sulfur fuels (HFO) to alternative fuels, i.e., low-sulfur fuels (LSF), but it takes up useful space on the ship due to the large size of the facilities (Abadie et al., 2017; Jiang et al., 2014; Panasiuk & Turkina, 2015). Ship type and its remaining lifetime are two determinant factors in opting for the scrubber installation. Ships with a longer lifetime and larger size are more suitable for installation of scrubbers (Lindstad et al., 2017; Zhao, Fan, et al., 2021). Jiang et al. (2014) propose four years as the remaining lifetime benchmark for installing a scrubber.

2.1.2. Alternative fuels, dual fuel engines

Using alternative fuel is also a feasible solution to improve energy efficiency in shipping. Marine gas oil (MGO) and liquefied natural gas (LNG) are two main alternative fuels that have already been developed and are available on the market (Zheng & Chen, 2018). Compared to MGO, LNG contains almost no sulfur and lower NOx (Brynolf et al., 2014). Abadie et al. (2017) reveal that the attractiveness of alternative fuels depends on the price spread between MGO and HFO. If the price spread between HFO and MGO goes down, the attractiveness of alternative fuels will increase. But at that moment, the attractiveness of using alternative fuels is still lower than installing scrubbers due to the high fuel cost (Zis & Psaraftis, 2017).

Concerned about uncertain fuel costs, the configuration of a dual fuel engine is introduced when building a new vessel, because it can run either in gas mode or diesel mode, which benefits shippers to convert fuels between HFO and LSF in terms of local port legislation (Abadie & Goicoechea, 2019; Brynolf et al., 2014).

2.1.3. Selective catalytic reduction and exhaust gas circulating system

To achieve NOx reduction compliance with Tier III engine requirements, Selective Catalytic Reduction (SCR) and Exhaust Gas Circulating (EGR) are two dominant options for stakeholders (Lloyd's Register, 2015). Technological maturity, system availability and costs are key determinants that may affect stakeholders' decisions. Both EGR and SCR are currently under development; the investment capital of SCR is slightly higher than that of EGR, but the technological uncertainty is greater than the price difference between them at the moment (DNV, 2020). Unlike the SCR, the EGR system is not restricted by reaction temperature or fuel sulfur content in NOx emissions reduction (Zhao, Fan, et al., 2021., Zhao, Wei, et al., 2021). It is worth noticing that the EGR may suffer from incomplete fuel combustion and may then increase CO and Particular Matter (PM) emissions (Fathi et al., 2011). Installing EGR with or without scrubbers is the most economical choice (Zhao, Fan, et al., 2021., Zhao, Wei, et al., 2021).

2.1.4. Battery propulsion, battery hybrid propulsion, fuel cell and nuclear propulsion

Electric or hybrid propulsion systems such as diesel-electric systems, batteries, and fuel cells enable propulsion from sources. Compared to conventional propulsion, electric/hybrid propulsion has higher energy efficiency, resulting in lower pollutant emission. Various types of ships can benefit from hybrid or electric propulsion. Specifically, short-sea transportation can benefit from all-electric ships, while offshore and passenger ships gain the most benefits from using electric and hybrid propulsion systems (Jafarzadeh & Schjølberg, 2018). To satisfy electric/hybrid propulsion usage, ports are required to be equipped with battery charging or hydrogen fueling supply infrastructure. This likely increases investment costs and administration costs for ports (Sciberras et al., 2017).

The concept of the fuel cell is analogous to electric/hybrid propulsion, which converts the chemical energy of reactants (e.g., hydrogen or hydrogen-rich fuels) into electrical energy (Jafarzadeh & Schjølberg, 2018; Science and Technology Committee, 2012). Many studies have represented the benefits of adopting fuel cells from different perspectives, such as public health benefits (Zhu et al., 2022), and energy efficiency (Jafarzadeh & Schjølberg, 2017). Due to regulatory gaps, this technology's application has not yet been widely applied to shipping (Inal & Deniz, 2020).

In addition to electric/hybrid propulsion and fuel cells, there is a growing interest in producing electricity using a renewable source - nuclear power (Balcombe et al., 2019; Ren & Lützen, 2017). Nuclear fuel takes advantage of a longer operating time (approximately 30 years) without refueling (Furfari & Mund, 2022). But there is still a long path for nuclear power navigation to be adopted in commercial, due to e.g., civilian evacuation plans and fears at docks (Balcombe et al., 2019).

2.1.5. Solar and wind hybrid auxiliary propulsion

Renewable energy has gradually drawn great attention in the shipping market. Solar panels and wind auxiliary propulsion have started to be considered due to their zero-carbon environmental impact. WindWings[1] from BAR is an example of combining wind propulsion with route optimization, which could improve fuel efficiency by more than 30 % depending on specific ship retrofitting and building cases. The initial cases are based on bulk carriers and tankers; it is expected that further variations will be designed and developed for other large ship types. Solar panels are more often used for short-sea vessels than ocean-going ships because their application is affected by various factors, such as environmental conditions, technical hindrances, and the low energy density they can produce or carry (Park et al., 2022).

2.2. Emission abatement technologies from port and land transportation

2.2.1. Port infrastructure

Based on the literature review of Alamoush et al. (2022), there are three main emission abatement solutions for portside activities: utilizing alternative cleaner fuel to run port equipment, converting power systems to electrification, and using renewable energy. Specifically, LNG bunkering stations and onshore power supply (OPS) are becoming the options for the developments of green ports (Peng et al., 2021; Zis, 2019). Those green infrastructures are available in the globally fortune ports (Poulsen et al., 2018). However, there are still many frontrunner ports challenged with implementing a shoreside electricity system due to the high investment requests on port infrastructure and complex connections (Lindstad et al., 2017).

2.2.2. Land transport

Land transport vehicles towards automation and digitalization operations have become increasingly concerned (Alamoush et al., 2020; Bjerkan & Seter, 2019). Intelligent automated vehicles with better maneuverability not only realize vehicle routing optimization but also enhance energy efficiency (Kavakeb et al., 2015). Also, intelligent automated vehicles can address manpower shortage issues, by their potential to pick up/drop off containers without direct human command (Bjerkan & Seter, 2019; Xin et al., 2014).

Mathematical modeling and simulation studies demonstrate that virtual systems that would coordinate truck and rail transport with vessel arrivals could collectively improve operational efficiency and reduce idling times and emissions at port for both vessels and inland transport (Shancita et al., 2014). However, limited empirical evidence of more efficient operations has been included so far.

2.3. Significant contribution to the implementation of IMO's emission reduction strategies: Norway and Singapore

The IMO has focused on international cooperation to ensure the effective adoption and implementation of emission reduction strategies. To ensure an appropriate level of emission reduction in the maritime

[1] BAR Technologies has invested significant resource over the past years to become equipped to become a key player in cutting emissions in the marine industry. That research resulted in the patent pended WindWings technology. Source: https://www.bartechnologies.uk/project/windwings/

industry, many countries have created and financed specialized projects in parallel with IMO regulations. The leading global projects Green-Voyage2050 and NextGEN Connect initiative are made by Norway and Singapore (Yeremenko, 2022).

Recently, IMO promoted the corporation between Norway and Singapore to widen the capability to implement IMO's emission reduction strategy. To understand the competitiveness of Norway and Singapore, this subsection provides a brief summary.

2.3.1. Norway model

In the green transition process, Norway is playing a leading role in the global maritime transport system (Tvedten & Bauer, 2022). The leading position of Norway is not only represented by its large proportion of advanced and specialized vessels, including the world's first battery-electric ferry. Its social-technological innovation business model also attracts international attention (Bach et al., 2020; Tvedten & Bauer, 2022).

To reach a green transition, Norway proposes the strategy of an actor-network, which is to involve several actors in the maritime industry to negotiate port fees and/or dues legislation (Bjerkan et al., 2021). Also, Norway invests in R&D and initiatives in a wide range of experiments to explore innovative resources and technologies (i.e., electrification) for sustainable green developments (Bjerkan & Ryghaug, 2021). The strengths and weaknesses of Norway's strategies are represented in Table 3.

2.3.2. Singapore model

Singapore is a globally leading container port and bunkering port. Singapore's economic prosperity benefits from its unique geographical position and market mechanisms (Schönsteiner et al., 2016). As one of the largest exporting refinery centers, Singapore plays an important role in international bunker supply, despite itself not being a major source of bunker fuel. The large amounts of transportation energy required thus heavily depend on energy imports.

Schönsteiner et al. (2016) point out that Singapore will lose its attractiveness if transport costs would increase due to the green transition. To maintain its competitiveness, Singapore policymakers focus on the economic feasibility of abatement technologies while starts green transition through a port dues concession initiative. The strengths and weaknesses of Singapore's strategies are represented in Table 4.

2.4. Sustainability criteria and indicators

Decisions on shipping finance and investment are mainly driven by economic and environmental factors (Alexandridis et al., 2018; Zhang et al., 2021). To achieve sustainability, decision science highlights the roles of social factors, such as public awareness, and social behavioral change (Bjerkan & Seter, 2019; Cinelli et al., 2014; Doukas & Nikas, 2020; Huang et al., 2011).

In this study, to assess the sustainability of various emission abatement technologies, we framed a set of technological, economic, environmental and social criteria and indicators with reference to Zhao et al. (2020).

The Analytic Hierarchy Process (AHP) (see Section 3) is implemented in this study to elicit the stakeholders' preferences on the emission abatement technology selection for the sea transport system. The research is conducted as shown in Fig. 1.

Table 3
The strength and weakness of Norway abatement strategy.

Norway model	
Strength	Weakness
• Clear political goals and emission regulation • Norwegian actors are central within the EU R&D network, actively patenting hydrogen and battery-electric technology • Good cooperation between several types of actors within regional and national networks • Wide range of experiments initiated by several types of actors • Relatively complete regulatory framework • Substantial public and private investments, such as NOx-fund, development contracts to promote capital and resource mobilization	• Due to technological uncertainty, large-scale technology need be tested and further developed • Need for education of on-board personnel for operation and maintenance • Lack of standardization, such as charging infrastructure • Complicated funding application process and lack of public funding for project continuation

Sources: Bach et al. (2020); Mäkitie et al. (2022); Tvedten and Bauer (2022).

Table 4
The strength and weakness of Singapore abatement strategy.

Singapore model	
Strengths	Weakness
• One of the busiest ports in the world, with an emphasis on high efficiency and productivity • Good collaboration between several transportation R&D projects within national and regional networks • Test bedding facilitates the commercialization process for new technologies to evaluate, pilot and commercialize • Public funding invests in exploring sustainable resources, such as biofuels, solar photovoltaic, and regional headquarters activities • Complete regulatory about carbon tax and application guidance	• Due to natural resource scarcity, sustainable technology needs to be explored and further developed • Loss of low-cost competitiveness • Loss of tax revenue

Sources: Schönsteiner et al. (2016); MPA (2017); MPA (2022).

3. Methodology: analytic hierarchy process (AHP)

Multi-criteria decision-making (MCDM) problems are usually raised in the activities subject to sorting, ranking, and selecting. It is a complex process to define and model the MCDM problems, as various actors, multiple criteria, and decision alternatives need to be considered. MCDA methods serve as valuable tools to support decision-makers in eliciting preferences and generating informed recommendations.

Analytic Hierarchy Process (AHP), proposed by Saaty (1980), is among the most widely used MCDA methods, particularly for technology assessment, as discussed in Section 1. However, despite its popularity, AHP is not without limitations. One significant drawback is the phenomenon of rank reversal, which has garnered considerable attention. Rank reversal occurs when the addition or removal of criteria or alternatives alters the ranking order of existing alternatives, leading to potentially inconsistent or counterintuitive outcomes (Maleki & Zahir, 2013). For example, if alternatives A, B, and C are initially ranked in that order, the introduction of a new alternative D might cause A and B to switch ranks, even if D is not directly comparable with them or does not offer any real competitive edge.

The primary causes of rank reversal in AHP include: (i) normalizationl; (ii) inconsistency in judgments, (iii) non-independences of alternatives. First, AHP relies on pairwise comparisons, where each alternative is compared with others according to criteria. These scores are subsequently normalized, leading to interdependent outcomes, meaning that changes to the set of alternatives (such as adding or removing one) can influence the relative weights due to normalization. Second, any slight inconsistencies can be amplified with the addition of new alternatives. This effect can lead to rank reversal when minor adjustments in preference weights cascade into a different overall ranking. Third, in AHP, alternatives may not be entirely independent due to the

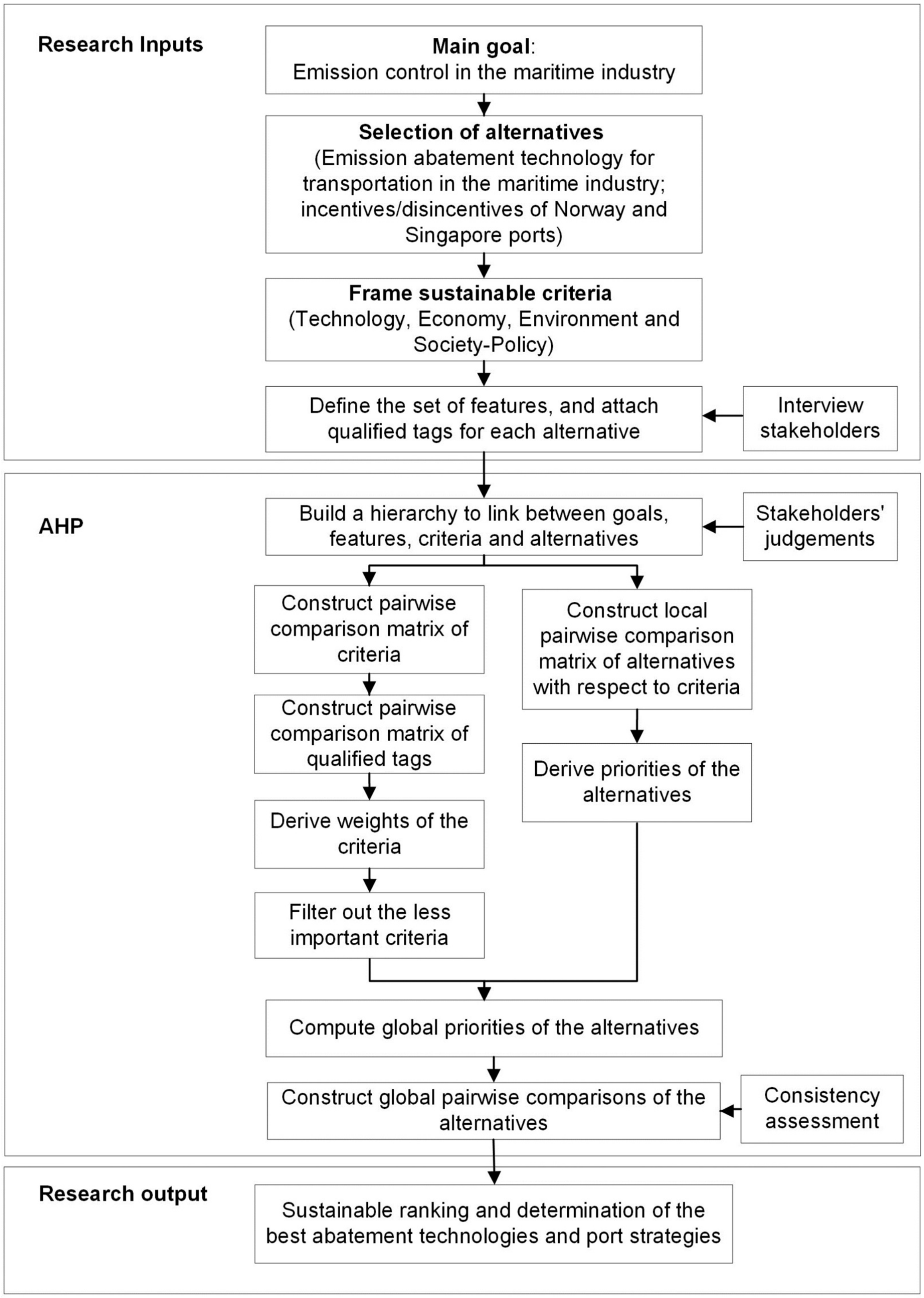

Fig. 1. Research protocol diagram.

relative nature of pairwise comparisons. Consequently, the addition of a new alternative can disrupt the established structure, resulting in rank shifts.

To address rank reversal, several studies have emphasized the refinement of aggregation methods and normalization processes (Forman & Peniwati, 1998; Grošelj & Zadnik Stirn, 2012; Krejčí & Stoklasa, 2018; Maleki & Zahir, 2013; Xu, 2000). Identifying optimal aggregation methods remains a central focus in research on rank reversal. Among the most widely used methods are the weighted arithmetic mean (WAM) and the weighted geometric mean (WGM).

The WAM method aggregates values by assigning weights to reflect their relative importance, making it suitable for criteria that align with additive relationships. In contrast, the WGM method aggregates a set of positive values by raising each value to a power proportional to its weight, favoring scenarios with multiplicative relationships—such as those involving ratios, rates, or percentages—where relative proportions among values are significant.

In a comparative study, Krejčí and Stoklasa (2018) demonstrate the advantages of using WGM over WAM for priority normalization. Escobar et al. (2004) further suggest that WAM is preferable for individual aggregation, while WGM is more suitable for group aggregation. Following Escobar et al. (2004), we have implemented the WGM method to derive priority vectors from pairwise comparisons (see Section 4.3 for a detailed discussion).

In most cases, the decision-making environment is usually dynamic and fuzzy. Decision-making is usually done with imprecise information. AHP has limitations in supporting decision-making in such complex scenarios (Raharjo et al., 2009). Fuzzy AHP is designed to solve decision-making problems under imprecision and uncertainty (Kubler et al., 2016; Liu et al., 2020; Wang et al., 2008). However, implementing the fuzzy AHP may result in a loss of precision in the decision-making process. Ahmed and Kilic (2019) shows the application of the fuzzy AHP may increase inconsistency levels.

In practice, preferences or choices can be influenced or conditioned by specific circumstances, requirements, or constraints. Efficient decision-making requires focusing on the most crucial criteria, followed by the least critical ones. As the most important factors which have a significant direct or indirect influence on the goal of the stakeholders. Ognjanović et al. (2013) propose Stratified Analytical Hierarchy Process (S-AHP) supported with the feature model to ensure that the most important criteria are addressed first. We inspired by the S-AHP and developed an AHP-based method to identify the leading factors on decision-making under different circumstance.

The structure of the AHP-based method is represented in Fig. 2. To this end, a high-level objective (level 1) is based on lower-level aspects (or features) in level 2 and criteria definitions in level 3. See also Fig. 2. In this study, a feature model is used to identify feasible solutions that are compatible with specific emission limit requirements. Then AHP is implemented to weigh the alternatives. Similar to Saaty's AHP (Saaty, 1980), the AHP-based method builds a pairwise comparison matrix in level 2 and layer 1 of level 3 for a group of alternatives based on their relative importance subject to aspects and criteria (see Definition 1 and Definition 2).

In contrast to Saaty's AHP (Saaty, 1980), the involvement of the cardinality-based feature model reduces the construction and calculation of massive pairwise comparison matrixes. The implementation of feature models requires decision-makers to qualitatively define the degree of alternatives subject to specific characteristics; this is a process to attach qualified tags, as presented in Level 3 in Fig. 2.

Definition 1 (Relative importance). When two objects or elements are compared according to a criterion C, we say that we are performing binary comparisons. Let $\underset{C}{\succ}$ be the binary relation "more preferred than" or "dominated". Let $\sim_C$ be the binary relation "indifference" (Saaty, 1987).

$$A_i \underset{C}{\succ} A_j \textit{ if and only if } P_C(A_i, A_j) > 1$$

$$A_i \underset{C}{\sim} A_j \textit{ if and only if } P_C(A_i, A_j) = 1 \ (1)$$

If $A_i \underset{C}{\succ} A_j$, we say that A_i is preferable than A_j with respect to criterion C. Thus P_C represents the preference for one alternative over other. This alternative (options) valuing process is done by decision-makers (stakeholders).

To obtain a scale of relative importance (or rank order) of a set of alternatives, the natural way is to make paired comparisons (Saaty, 1987). The rank of alternatives is derived from decision-makers' prior knowledge, which is also called expectation. The expectation is allowed to be reflected by means of a positive number (1, 3, 5, 7 and 9), as shown

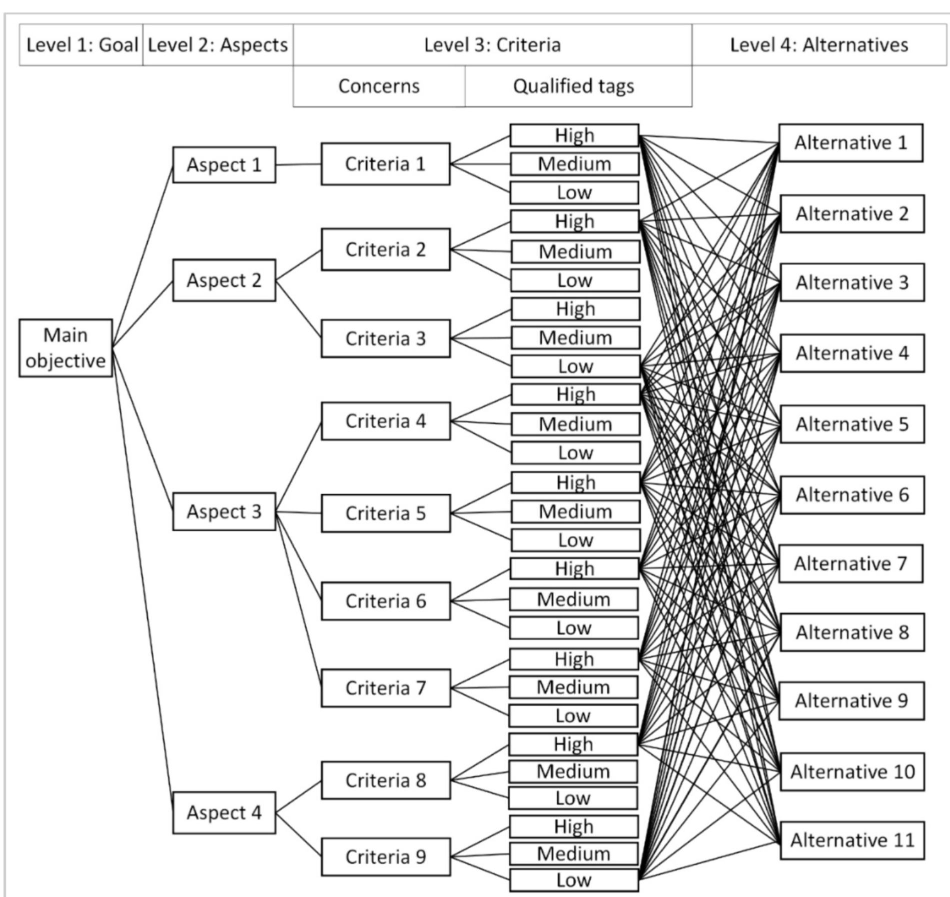

Fig. 2. Decision hierarchy diagram.

in Table 5.

Definition 2 (Matrix of relative importance). After a paired reciprocal comparison, a comparison matrix can be formed. Assuming we are dealing with n criteria in a given hierarchy, a pairwise $(n \text{ x } n)$ comparison matrix, A is established to quantify the decision maker's judgment of the relative importance of the criteria. The pairwise comparison is made such that the criterion in row i $(i = 1, 2, \ldots, n)$ and columns j $(j = 1, 2, \ldots, n)$ is ranked relative to other criterion. Let $a_{i,j}$ define the element (i,j) of the matrix A, thus the relative importance matrix can be presented as:

$$A_{nxn} = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix}. \tag{2}$$

Consistency in judgment means that if $a_{i,j} = k$, then $a_{i,j} = \frac{1}{k}$. Also, all the diagonal elements $a_{i,i}$ of an equal 1, because these elements rank each criterion against itself. Mathematically, we say that a comparison matrix A is consistent if,

$$a_{ij}a_{jk} = a_{jk}, \textit{for all } i, j, k. \tag{3}$$

Based on the stakeholders' judgments of each alternative in terms of aspect and criteria, the priority weight of relative importance matrix can be derived from Eq. (4):

$$\omega_{ij} = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)}. \tag{4}$$

Thus, the normalized matrix A' is obtained:

$$A'_{nxn} = \begin{pmatrix} \omega_1 & \omega_1 & \cdots & \omega_1 \\ \omega_2 & \omega_2 & & \omega_2 \\ \vdots & & \ddots & \vdots \\ \omega_n & \omega_n & \cdots & \omega_n \end{pmatrix}. \tag{6}$$

We get the priority weight of the aspect p_m $(m = 1, 2, \ldots, m)$, the priority weight of the criteria p_C $(c = 1, 2, \ldots, c)$, and the priority weight of alternatives $p_a (a = 1, 2, \ldots, a)$. The score of each alternative can be calculated by the production of p_m, p_c, p_a in each level.

4. Implementation

In this subsection, we represent how we implemented the AHP-based method. Section 4.1 presents our data collection method. The stakeholders' preferences for emission abatement alternatives clearly depend on the circumstances. Therefore, we constructed a feature model of the sea transport system in Section 4.2. An AHP-based method was utilized to further process the data as in Section 4.3. Section 4.4 represents results and discussions.

Table 5
The linguistic terms and the corresponding numbers for pairwise comparison.

Value of $a_{i,j}$	Scales
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate value	2, 4, 6, 8

(Source: adapted from Saaty (1987))

4.1. Data collection

Air pollution policy is informed by the International Convention for the Prevention of Pollution from Ships (MARPOL) regulation, in particular MARPOL Annex VI, which entered into force on May 19, 2005 (IMO, 2020). Regulation 13 (limits on NOx) and Regulation 14 (limits on SOx) of MARPOL Annex VI are the two predominant chapters for ships, adopted in 2011 (IMO, 2020).

This regulation provides guidelines for air pollution control measures that are introduced by national governments (Wang et al., 2023). As the guidelines do not stipulate by which technologies these stricter requirements can be met (Brynolf et al., 2014; Peng et al., 2021; Schinas & Stefanakos, 2014; Yang et al., 2012), the question arises which emission abatement technologies should be selected for compliance with MARPOL Annex VI?

Air pollution control methods differ in their benefits and disadvantages, and this can further depend on the time scale and state of various internal and external factors. Emission abatement technology selection, to some extent, is also informed by social expectations towards future development as well by national, international, and commercial interests. The lack of historical data is a challenge to the selection problem. When there is insufficient data, the knowledge and experience of stakeholders can provide valuable and insightful information for decision-making. The stakeholder plays an important role in providing qualitative and quantitative information to ensure the quality of the maritime regulatory process within the IMO or other regulatory authorities (Karahalios, 2017).

Accordingly, in 2019, we conducted a study to explore different green transition methods from shipping, ship-port interface, and port-side via collaboration with a ship owner, a ship operator, and a port operator. In a workshop, we wanted to identify the attendees' preferences for different types of air pollution control technologies. We took the green development paths in Norway and Singapore, whose ports and emission abatement technologies are world leading, as benchmark case studies around which the discussions were held (recall Section 2.3).

The workshop was designed to elicit diverse perspectives from stakeholders on the evaluation and selection of emission abatement technologies. We employed the Decision structuring dialogue (DSD) method to facilitate collective framing the complex and conflicting problem, see e.g., Slotte and Hämäläinen (2015). The decision structuring dialogue method begins with a facilitator introducing the skills and rules of dialogue, which help participants shift from conflicting and competitive positions to collaborative engagement. The essential dialogical skills in DSD include listening, inquiry, thinking together, suspending judgment, and expressing viewpoints appropriately. For effective dialogue, the facilitator not only encourages adherence to these skills but actively supports the group in following the rules, see as Phillips and Phillips (1993) and Papamichai et al. (2007).

Following an introduction to the dialogue skills and rules, stakeholders began discussions centered around the question: "Which types of emission abatement technologies are you most open to adopting for controlling air pollutants (NOx, SOx, PM2.5, CO2), and why? A foundational principle of DSD is the emphasis on "speaking from experience.". Observations during the workshop revealed that participants found it easier to accept an individual's lived experience rather than interpret the person's perspective as objective truth. This approach's effectiveness, validated by Boele (1998), facilitates greater acceptance and understanding among participants.

Following this problem-framing exercise, we intended to apply the Analytical Hierarchy Process (AHP) to evaluate participant preferences across various technologies. However, insights from the workshop revealed limitations in using traditional AHP for this purpose. The broad array of options proposed by participants introduced complexities, as AHP requires numerous pairwise comparisons, leading to significant computational demands. Additionally, certain options could be combined to address multiple pollutants, with potential combinations expanding as the number of technologies grows. This complexity calls for a more robust filtering approach to streamline the selection and elimination of abatement options, accounting for specific features and operational constraints to avoid overwhelming pairwise comparisons and calculations.

To address this, we implemented a feature model that allows participants to customize options based on specific needs and requirements. Adopting Felfernig et al.'s (2024) definition, we define a "feature" as an incremental aspect of a program or product's functionality. This approach refines the selection process by enabling constraints based on specified features. The feature model enables stakeholders to set minimum requirements, which helps exclude non-qualifying options and reduces the calculation demands of pairwise comparisons.

Through coding the dialogue documents collected from the

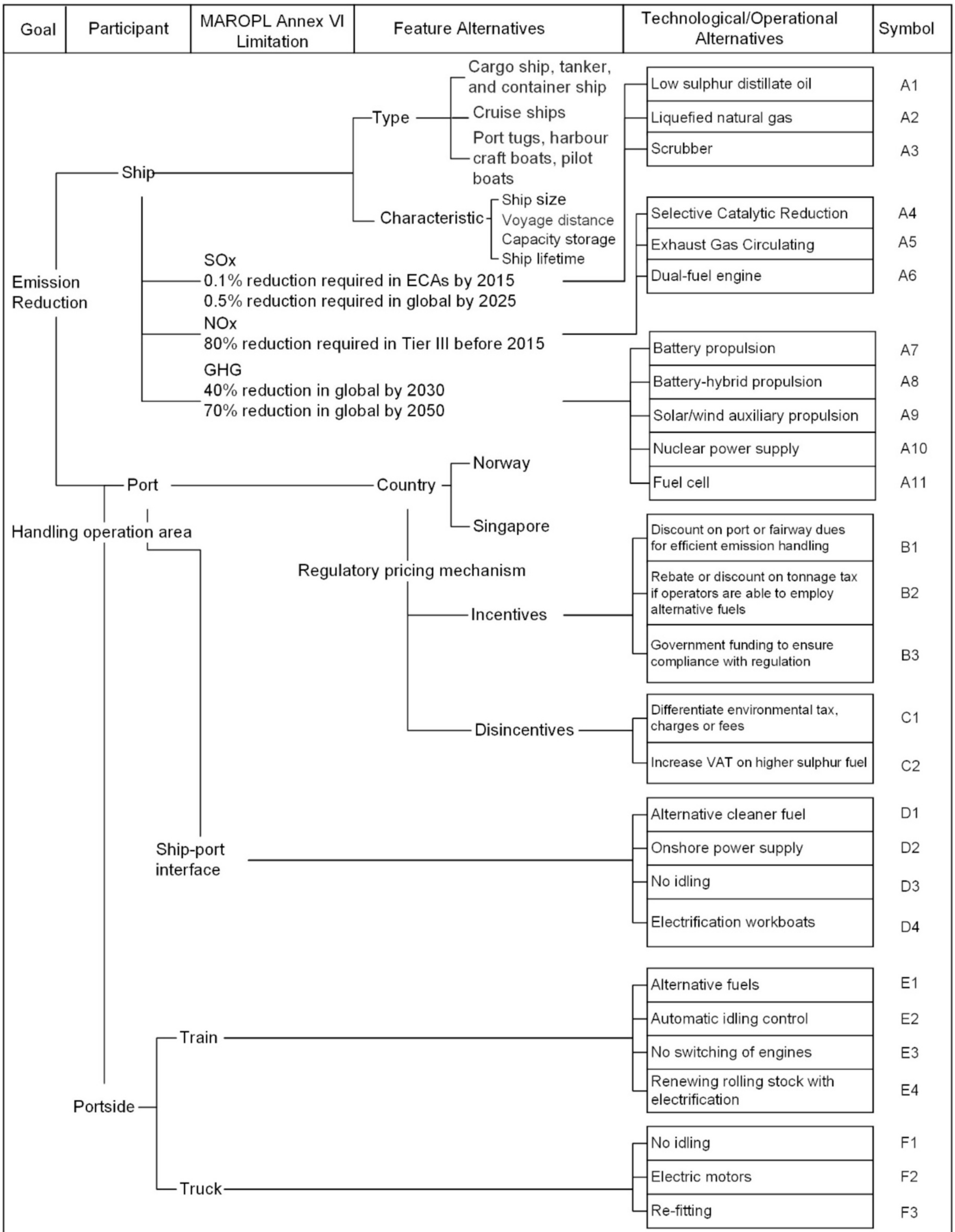

Fig. 3. A feature model for abatement technologies and green strategies selection.

workshop, we identified requirements a shortlisted alternative. These findings on technologies were subsequently presented to an experienced shipbuilding engineer to aid in structuring the technological pathways (see Fig. 3 for further details). AHP was then applied to these findings to rank the alternatives (see Section 4.3 for more information on expert scoring).

4.2. Alternatives selection and decision criteria

A feature model is formulated to support technology selection as depicted in Fig. 3. A feature model is a tool to visualize how possible solutions may help towards achieving various goals, see also Ognjanović et al. (2013).

Port emissions come from three main modes of transportation: shipping, train, and rail. From the stakeholders' perspective, the technology selection behavior of most ship owners in the current market is regulation oriented. The MARPOL protocol, ship type and ship lifecycle are the vital factors impacting the green transition speed for shipping. From a spatial perspective, offshore, ship-port interface, and portside are three main areas that lead to air emissions due to handling operations. Accordingly, Fig. 3 represents the hierarchy development of twenty-seven potential alternatives towards establishing the goals of emission reduction.

The general lifetime of vessels are 25–30 years. In this study, vessels built before 2016 were regarded as old vessels. Retrofitting is the feasible solution for the old vessels; vessels built after 2016 were regarded as new vessels. New design vessels have relatively more options for emission reductions compared with old vessels retrofitting.

Large-size merchant ships (i.e., cargo ship, tanker, and container ship) are usually used for long distance shipping. Passenger vessels, especially cruise vessels, are a very specialized group of ships, making it difficult to define a set of standard technologies they would apply. The new technologies embraced in the cruise ships are discussed in Section 4.4.1.

Most current large-size ships are fueled by heavy fuel oil (HFO). The HFO-fueled ships are predominately challenging with regulation 14 (SOx limits) and Regulation 13 (NOx limits) of MARPOL Annex VI. Thus, HFO-fueled ships are selected as reference to discuss feasible solutions for green transitions. Installing scrubbers and using alternative fuels, i.e., low sulfur distillate oil or liquified natural gas are feasible options to comply with SOx limit. To comply with NOx limit, installing selective catalytic reduction, exhaust gas circulating, or due-fuel engine are major solutions.

Small-size ships (e.g., port tugs, small ferries) are generally used for short distance shipping. GHG strategy highlight on reduce emissions from port area. Small-sized ships play vital roles in connecting the large-size merchant ships and ports. Therefore, we focus on exploring feasible solutions to reduce CO_2 from small-sized ships. From the stakeholder perspectives, using renewable fuels are feasible options. Therefore, five renewable fuels are discussed in this study.

In addition, Singapore model and Norway model are selected as two references model. The assumption is Singapore model provides a welcoming business environment to the shipping industry, such as by incentivizing port capacity growth, reducing emissions requirements of vessels at berth, and using its lobbying power to slow the introduction of new, more stringent IMO environmental standards in ports globally, while the Norway model provides a flexible R&D environment, such as creating and enforcing more stringent maritime emission standards in ports and partnering with other IMO nations to toughen new environmental standards, different incentives and disincentives were elicited via discussion. Naturally, some incentives will work well for both models. Stakeholders were required to evaluate incentive pricing and penalty pricing strategies based on the assumptions.

After determining the compatible options by the feature model, the next step is to determine evaluation criteria. This study adopts the evaluation criteria system provided by Ren and Lützen (2017). Table 6 represents the proposed decision hierarchy with three levels. The first level states the main criterion of achieving emission reductions in the maritime sector. At the lower level two, this breaks down into technological, economic, environmental, and social-political objectives. At the lowest level three, this produces in total nine criteria. Pairwise comparisons are then utilized to weight the alternatives in terms of the series of sustainable aspects and criteria.

Table 6
Decision hierarchy: criteria for sustainability evaluation.

Objective	Aspect	Criteria	Abbreviation
Level 1	Level 2	Level 3	
Emission reduction in maritime industry	Technical (T)	Technical maturity	T1
	Economic (EC)	Investment cost	EC1
		Operational cost	EC2
	Environmental (EN)	Effect on SOx reduction	EN1
		Effect on NOx reduction	EN2
		Effect on CO_2 reduction	EN3
		Effect on PM reduction	EN4
	Social-political (SP)	Government support	SP1
		Social acceptability	SP2

4.3. Pairwise comparisons

The pairwise comparison matrix is established to compare the pairs of criteria from the top level (level 2) to the low level (level 3). The templates are presented in Table 7 and Table 8. The pairs of alternatives are compared based on the nine criteria, respectively. An example is presented in Table 9.

We utilized AHP-OS, an open-source, web-based software designed for the AHP, which enables users to perform pairwise comparisons and calculate consistency ratios (CR) directly. Participants, who had been trained in AHP methodology, were provided with a link to complete individual comparison matrices. AHP-OS allows users to promptly review their judgments, identify inconsistencies, and suggests adjustments to improve consistency.

AHP-OS serves as a powerful tool for facilitating group decision-making. It not only supports the generation of a consensus result for AHP but also offers different aggregation algorithms, e.g. traditional AHP linear, geometric, and logarithmic scales, to synthesize participants' pairwise comparison matrices. In this study, results were derived and aggregated using the geometric scale, as the Weighted Geometric Mean (WGM) is well-suited for aggregating group judgments, as discussed in Section 3.

In response to the reviewers' suggestions for enhancing Saaty's AHP method for handling large-scale evaluation criteria, we propose utilizing the Pareto Principle (80/20 rule) to limit the number of criteria. The assumption of the Pareto principle is that approximately 20 % of criteria typically drive around 80 % of decision outcomes. This approach has been demonstrated in studies by Kharub et al. (2022), Potomkin et al. (2021), and Duleba and Moslem (2019).

Using the data in Fig. 4 as an illustrative example, criteria EN1, EN2, and EN3 emerge as the most influential, exceeding the 80 % threshold. Consequently, criteria other than EN1, EN2, EN3, SP1, EC1, and EC2 can

Table 7
Pairwise comparison matrix of aspect in level 2: a template.

Concerns/aspects	T	EC	EN	SP
Technical efficiency (TE)	1			
Cost efficiency (CE)		1		
Environmental efficiency (EE)			1	
Social-Political (SP)				1

Table 8
Pairwise comparison matrix of criteria in level 3: a template.

(a) Pairwise comparison matrix of the first cluster in level 3.

Technological aspect (T)	T1
T1	1

(b) Pairwise comparison matrix of the second cluster in level 3: a template.

Economic aspect (CE)	EC1	EC2
EC1	1	
EC2		1

(c) Pairwise comparison matrix of the third cluster in level 3: a template.

Environmental aspect (EE)	EN1	EN2	EN3	EN4
EN1	1			
EN2		1		
EN3			1	
EN4				1

(d) Pairwise comparison matrix of the fourth cluster in level 3: a template.

Social-political aspect (SP)	SP1	SP2
SP1	1	
SP2		1

Table 9
Pairwise comparison matrix of compatible alternatives based on T1 criteria.

T1	A1	A2	A3
A1	1		
A2		1	
A3			1

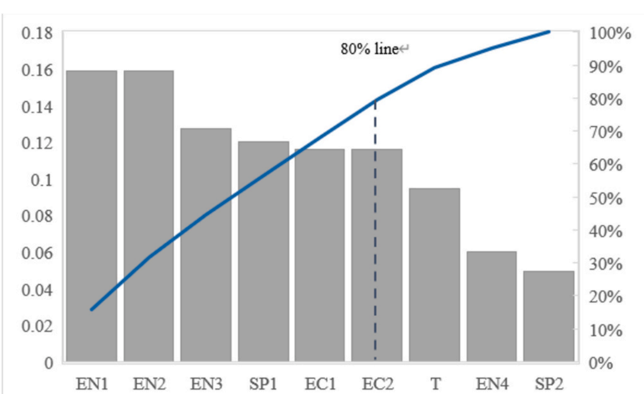

Fig. 4. Example: Pareto chart of criteria weights.

be considered for exclusion from the analysis. Notably, the exclusion of criteria requires adjustments to the remaining weights. In this example, the initial weights of EN1 (0.1587), EN2 (0.1587), EN3 (0.1271), SP1 (0.1204), EC1 (0.1158), EC2 (0.1158) their weights should be summed and normalized. Therefore, the adjusted weights are EN1 ($0.1992 = \frac{0.1587}{0.1587+0.1587+0.1271+0.1204+0.1158+0.1158}$), EN2 (0.1992), EN3 (0.1596), SP1 (0.1512), EC1 (0.1454), EC2(0.1454).

In this study, we apply the Pareto principle to identify the influential criteria in Norway and Singapore model, see Section 4.4.2.

4.4. Results and discussions

Scenario analysis has been widely used by major institutions when analyzing future energy development (Breyer, 2020). Stakeholders discuss preferences in different scenarios. We summarize the results in Section 4.4.1 and Section 4.4.2.

Overall, the maximum consistency ratio (CR) obtained was 0.67, demonstrating consistency across all participants' judgments.

4.4.1. Emission abatement technology selection for shipping

The selection of alternative fuels and power systems mainly depends on ship characteristics. The results of the qualitative analysis are summarized in Table 10.

Fig. 5 and Fig. 6 show stakeholders' preferences for different emission technologies. The total weights for each option are listed in Table 11. To clarify how this study contributes to technology selection in shipping, we compare the feature selection in this study with the existing literature. The comparison results are presented in Table 12.

Fig. 5 presents a radar chart comparing stakeholder preferences for various emission abatement technologies across multiple criteria for different vessel types. Scenario 1 illustrates stakeholder preference weights for retrofitting older large-size vessels (solid lines), whereas scenario 2 depicts preferences for new large-size vessels (dashed lines).

For older large-size vessels, there is a focus on mature, cost-effective solutions. Technologies such as scrubbers and LSDO offer a balance between emission reduction and manageable costs, making them well-suited for retrofitting on older vessels with limited cargo capacity. However, from a long-term perspective, these options may not meet the highest environmental standards required for new vessels, as they have limited effect on CO_2 reduction (see Table 10). Conversely, emerging technologies, such as solar/wind and nuclear power, align more closely with future environmental goals but face adoption challenges related to technological maturity, cost, and cargo capacity limitations.

Both LNG and dual-fuel engines demonstrate strong potential for both retrofitting and new installations due to their robust emission reduction capabilities. LNG, in particular, offers substantial environmental benefits in terms of GHG reduction and receives higher preference weights in criteria like government support and social acceptability (refer to Table 10 and Fig. 5), underscoring its suitability for new vessels that meet future regulatory standards. Dual-fuel engines offer flexibility in fuel selection.

Furthermore, SCR and EGR are suitable for targeted applications focused on NOx reduction, though they may be less favorable for widespread adoption (see Table 10 and Fig. 5). Stakeholders have suggested profiles to expand the application of SCR and EGR. For instance, installing a "scrubber and EGR" on HFO-powered ships with adequate storage capacity is presently a viable solution for meeting evolving SOx and NOx limits. However, as with LSDO, "scrubber and EGR" installations may expose ship owners to compliance risks if more stringent GHG strategies are implemented in the future.

Fig. 6 presents a radar chart comparing three emission abatement technologies—battery, battery hybrid, and fuel cell—across multiple criteria under two scenarios. Scenario 3 illustrates stakeholder preference weights for retrofitting older short-distance shipping vessels (solid lines for battery and battery hybrid), while scenario 4 represents preference weights for implementing these technologies on new short-distance vessels (dashed lines for all three technologies, with the fuel cell only considered in scenario 4).

Overall, the battery and battery hybrid technologies exhibit higher maturity scores, indicating their suitability for immediate implementation. In contrast, fuel cell technology, shown exclusively for new vessels, is considered more appropriate for forward-looking projects rather than retrofits.

Battery technology is highly favored in both retrofitting and new installation scenarios for its emission reduction capabilities, making it ideal for applications where environmental performance is crucial. Fuel

Table 10
Feasible solutions for ship emission abatement.

Option	Technological factors	Economic factors		Environmental factors				Other factors	
	Technology maturity	Capital investments	Operating costs	SOx	NOx	PM	CO_2	Cargo capacity	Voyage distance
HFO	Very Mature	Low	Low	–	–	–	–	Unrestricted	Long
A1:LSDO	Very Mature	Slightly high	Low	+	–	–	–	Unrestricted	Long
A2: Scrubber	Very Mature	High	Low	+	–	–	–	Restricted	Long
A3: LNG	Slightly Mature	Very high	Very high	++	++	++	++	Restricted	Long/short
A4: SCR	Very Mature	High	Low	–	+	–	–	Restricted	Long
A5: EGR	Very Mature	High	Low	–	+	–	–	Restricted	Long
A6: Dual-fuel engine	Slightly Mature	Very High	High	+	+	+	+	Restricted	Long/short
A7: Solar/Wind	On development	Very high	Low	+	+	+	+	Restricted	Long
A8: Battery propulsion	Mature	Very high	Low	+++	+++	+++	+++	Restricted	Short
A9: Battery hybrid	Slightly Mature	Very high	Low	++	++	++	++	Slightly restricted	Short
A10: Nuclear-powered	On development	Very high	high	++	++	++	++	Restricted	Long
A11: Fuel cell	On development	Very high	Very high	+	–	+	–	Restricted	Short

Note: +: positive effect on emission reduction; –: negative effect on emission reduction.
Sources: developed from stakeholders meeting, see Section 4.2, and Chu Van et al. (2019).

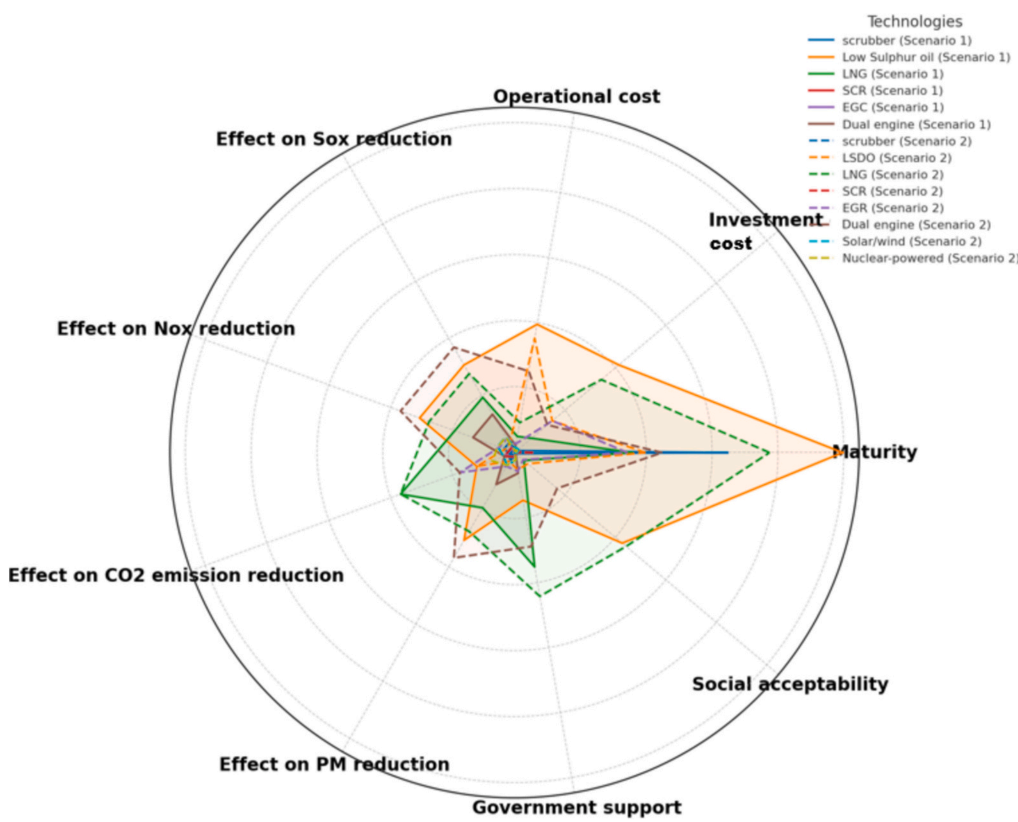

Fig. 5. Preference weights of alternatives for long-distance shipping.

cell technology, meanwhile, is evaluated solely for new short-distance vessels, reflecting its status as an emerging option. Its lower scores in government support and social acceptability suggest potential challenges in current adoption, yet it may offer significant promise as the technology matures and receives greater regulatory support.

Fuel cells are usually fed by natural gas, but different fuels (e.g., hydrogen, ammonia, methanol, LNG, and biofuel). It is theoretically feasible to use methanol fuel cells, and the usage of methanol fuel cells requires emission-free CO_2 storage. From the stakeholders' perspectives, liquid hydrogen is suitable for shorter distance travelling ships, but it requires to more space for storage which reduces cargo capacity. In addition, the combustion of hydrogen may produce NOx at certain temperatures because of the nitrogen content of the air. An ammonia fuel cell is thus a preferable option with respect to the demand for saving capacity. The major safety issue of fuel cell is related to leakage risk in the pipes during high-temperature exhaust gases and electricity production (Inal & Deniz, 2020).

Cruise vessels as a particular type of ship is highlighted by the stakeholders. From the stakeholders' perspective, electrification for cruise ships is possible. However, the electric battery cruise ships may be challenged with charging issues and voltage mismatch problems. Most importantly, some of the small ports that the cruise ships visited have not yet constructed the onshore power system (OPS). Regarding the battery usage on the cruise ship, the battery is better used throughout the journeys to shave off peak energy needs. Regard as fuel cell, waste foods are considered as a possible biofuel. This requires the cruise ship to install biodigesters and dehydrators so that to recycle the waste foods and generate the biofuel.

Table 12 shows that technology selection, subject to ship type and voyage distance, has been widely studied and discussed. However, few

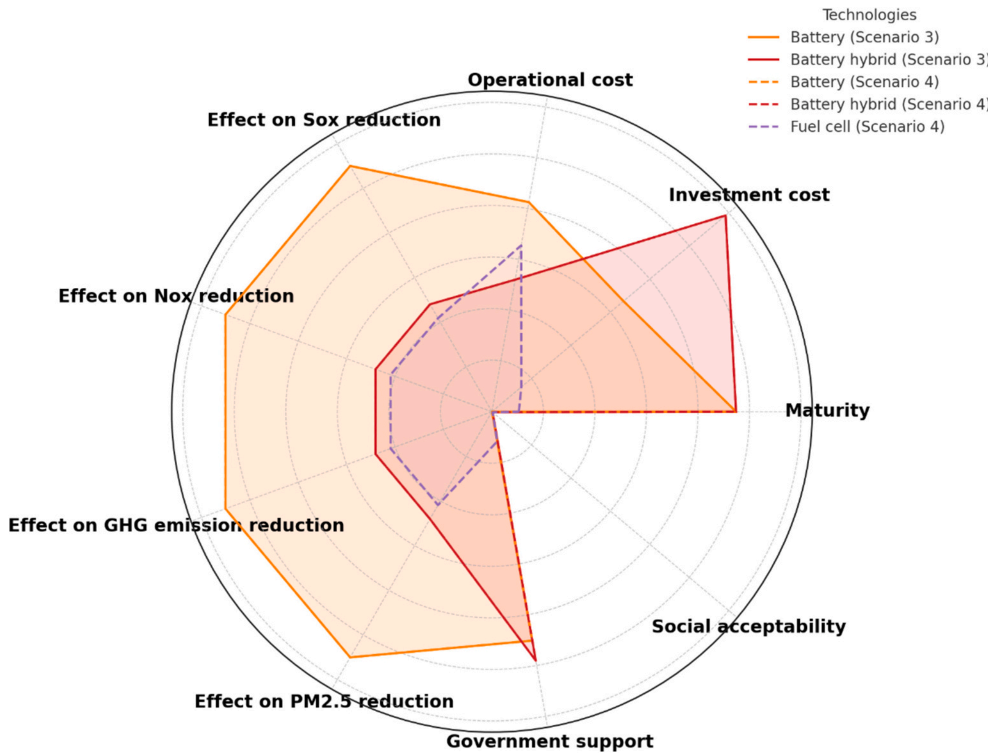

Fig. 6. Preference weights of alternatives for short-distance shipping.

Table 11
Decision-making matrix of technologies (alternatives) for ships.

Ship	Scores	Rank	Scores	Rank	Scores	Rank	Scores	Rank
Features								
Ship type	Large		Large		Small		Small	
Voyage distance type	Long-sea shipping		Long-sea shipping		Short-sea shipping		Short-sea shipping	
Ship lifecycle	Old		New		Old		New	
Regulation of MARPOL Annex VI 14 SOx compliance options								
A1: Scrubber	0.3233	2	0.1989	3	–		–	
A2: low-sulfur oil	0.4982	1	0.3872	2	–		–	
A3: LNG	0.1785	3	0.4139	1	–		1	1
Regulation of MARPOL Annex VI 13 NOx compliance options								
A4: SCR	0.1715	3	0.1715	3	–		–	
A5: EGR	0.2244	2	0.2244	2	–		–	
A6: Dual fuel engine	0.6996	1	0.6996	1	–		1	1
GHG compliance options								
A7: Battery propulsion	–		–		0.3554	2	0.4502	1
A8: Battery hybrid					0.6204	1	0.3841	2
A9: Fuel cell	–		–		–		0.1415	3
A10: Solar/wind	1	1	0.5126	1	–			
A11: Nuclear power	–		0.3755	2	–			

studies consider ship lifetime, ship size, and technology lifetime. This study contributes to expanding the scope of the existing literature by discussing the technology selection in terms of different types of ships.

4.4.2. Portside sustainability technology and strategy selection

Ports play a vital role in speeding the green transition, which reflects not only on the portside but also on hinterland transport operations and shipping at both the local and global levels. Regarding incentives and grants, Table 13 shows preference weights on the Norway model and the Singapore model subject to their incentive pricing and penalty pricing strategies of. In Table 13, government funding and differentiated environmental tax, charges are respectively as preferable incentives and grants.

Port operations are subject to interaction with transport chains, ranging from inland waterways, domestic, and oceangoing vessels to land transport (such as trucks, locomotives, and railways). Most of these activities depend on fossil fuel, and also consume large amount of energy, thus generating considerable GHG emissions. To facilitate adoption of low emission technologies among port, truck and train owners, the scores and rankings of feasible options in ship-port area are summarized in Table 14 - Table 16. (See Table 15.)

Through Pareto analysis, we identified government support as a critical factor for the successful implementation of this initiative. To illustrate stakeholder preference weights regarding government support for each port technology, we present a diverging bar chart comparing the Singapore and Norway models, as presented in Fig. 7. The length and color of each bar represent the degree to which stakeholders in either the Singapore or Norway model prioritize a particular technology, allowing

Table 12
Comparison analysis of studies related to alternative fuels and power system selection for maritime transportation.

References	Feature selection						Case study
	Ship type	Ship Lifetime	Ship size	Cargo capacity storage	Voyage distance	Technology Lifetime	
Rivarolo et al. (2023)	✔	✔	✔	✔			✔
Korberg et al. (2021)	✔		✔	✔	✔	✔	✔
Aspen and Sparrevik (2020)				✔	✔		✔
Tan et al. (2020)	✔			✔	✔		✔
Inal and Deniz (2020)				✔		✔	✔
Iannaccone et al. (2020)	✔		✔		✔		✔
Ammar (2019)	✔			✔	✔		✔
Chu Van et al. (2019)	✔			✔	✔		✔
Lindstad and Eskeland (2016)	✔						✔
This study	✔	✔	✔	✔	✔		✔

Table 13
The scores and ranking of strategies (alternatives).

Green strategies	Norway model	Rank	Singapore model	Rank
Incentive pricing				
B1: Discount on port or fairway dues for efficient emission handling	0.3645	2	0.073	3
B2: Rebate or discount on tonnage tax if operators are able to employ alternative fuels	0.2891	3	0.077	2
B3: Government funding on ensuring compliance with regulations	0.3464	1	0.120	1
Penalty pricing				
C1: Differentiate Environmental tax, fees or chargers	0.5936	1	0.5132	1
C2: Increase VAT on higher sulfur fuel	0.2948	2	0.2924	2

Table 14
The scores and ranking of technologies (alternatives) for ports.

Port	Norway model	Rank	Singapore model	Rank
D1: Alternative cleaner fuel	0.2695	2	0.2352	3
D2: Onshore power system (OPS)	0.2077	3	0.2443	2
D3: Electrification workboat	0.3331	1	0.2519	1
D4: No idling	0.1744	4	0.1667	4

Table 15
The scores and ranking of technologies (alternatives) for train at portside.

Train	Norway model	Rank	Singapore model	Rank
E1: Alternative fuels	0.2206	3	0.2494	3
E2: Automated idling control	0.2352	2	0.2675	2
E3: No switching of engines	0.1957	4	0.1923	4
E4: Renewing rolling stock with electric	0.2990	1	0.3466	1

Table 16
The scores and ranking of technologies (alternatives) for truck at portside.

Truck	Norway model	Rank	Singapore model	Rank
F1: No idling	0.4059	1	0.3528	1
F2: Electric motors	0.2931	3	0.2786	3
F3: Hybrid-electric trucks	0.3010	2	0.2820	2

for a clear visual comparison of preferences across the two models.

In Fig. 7, electrification workboats (e.g., battery-electric craft boats or pilot boats) exhibits the largest positive difference, suggesting that this option is comparatively more favorable for stakeholders in the Singapore model than in the Norway model. This might be explained by their geographic locations. The performance of lithium-ion batteries is very sensitive to temperature; the operating temperature range for electric vehicles should be kept between 15 °C and 35 °C; and extremely cold weather could lead to adverse effects on the lithium-ion batteries (Kim et al., 2019). Compared with Norway, Singapore can provide a suitable operating temperature for the electric workboat and vehicle. Based on this reason, the hybrid-electric trucks (traditional diesel-based forklift trucks) are preferable to the battery-electronic trucks in both Norway and Singapore model (see Table 16).

Waiting time for charging or refueling is another important consideration by the stakeholders' preferences (Solvi Hoen et al., 2023). Electric-battery workboats require more frequent "fueling" compared to diesel-fueled workboats. Specifically, electric battery pilot boats usually require 8–12 h of charging and can last for 8–12 h. In comparison, workboats fueled by diesel may be operational for 10 consecutive days and require only 2 h refueling time. More frequent charging of electric-battery boats is expected when the battery degrades. Additional training of the crew to work with electrification and batteries is needed because this is DC power and not AC power. Special crew training is required, and the higher training level makes these individuals more valuable in the employment market and thus can command higher wages.

Using alternative fuel is considered as another feasible solution. There is a heated discussion about which alternative fuel can be used for workboats. In the short term, LNG might be a feasible solution. In the long term, green diesel, for example, C14-C16, seems to be a promising option due to its low investment capital. The principle of green diesel is to use hydrogen as an input and mixed with CO_2 from the air through a production facility that would produce synthetically made C14 and C16 kinds of green diesel (Velpuri et al., 2023). But the green diesel is not yet there. Alternatively, fuel cells, ammonia, or methanol are too dangerous to be used in exclusion zones in ports. Biofuel is also not a feasible solution for the workboats due to its insufficient performance and high investment capital.

Biodegradable lubricants are a feasible solution for pilot boats and tugs when not undertaking urgent work, such as hull cleaning, propellor polishing with robots, or low speed whenever possible. Biodegradable lubricants benefit machines by keeping them in optimal conditions (reducing start-up emissions by keeping machines warm with, e.g., shore supply at low voltage).

When it comes to discussing port infrastructure, onshore power supply (OPS), or cold ironing appears to be a preferable option (see Table 14). During berths, ships generate pollutant emissions and noise

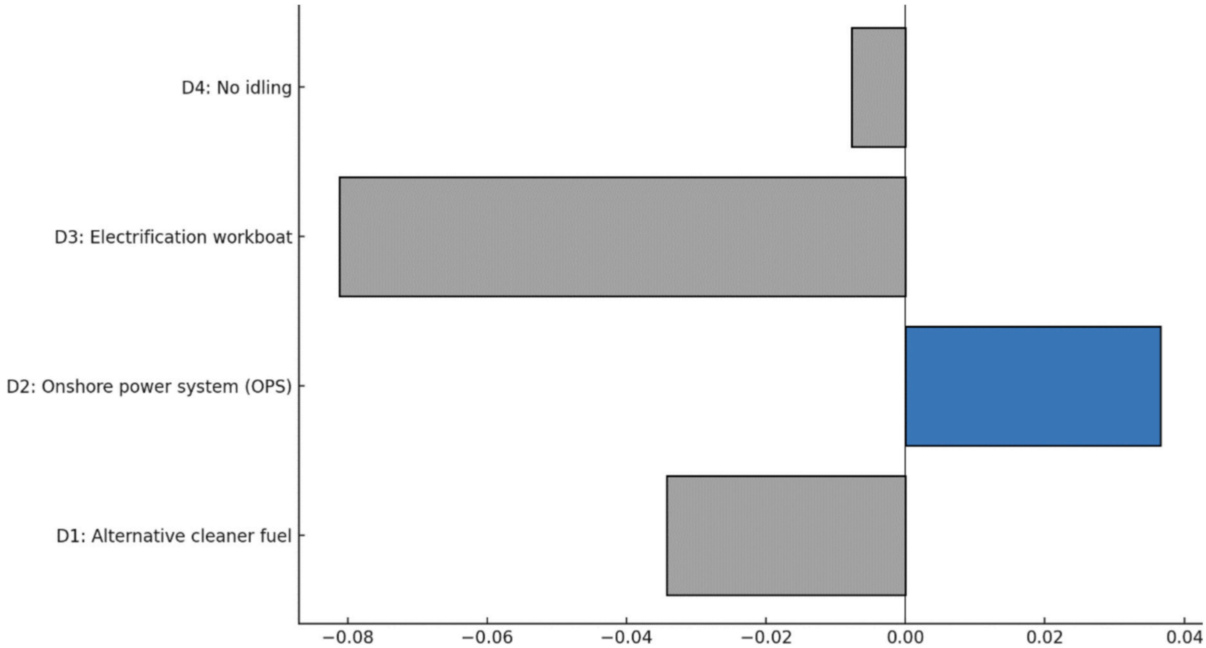

Fig. 7. Differences in preference of port alternatives based on government support criterion in the Norway model (blue bars) and Singapore model (grey bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

since auxiliary engines keep working to support some basic functions. OPS not only reduces air pollution produced from diesel generators but also reduces noise. When designing an OPS system, many parameters need to be considered, such as the variations in power, voltage, and frequency levels in different parts of the world, in order to allow various types of ships from different regions and nations to berth and plug into onshore electricity grids.

5. Conclusions

This study evaluates different emission abatement technologies (options) in the sea transport system (i.e., shipping, train, truck, port) using the Analytic Hierarchy Process (AHP)-based method. AHP gave insights on how to define and model the technology evaluation in a group with relevant stakeholders. Considering there is no one-fit-all solutions, this study involves feature selection to support decision-makers with insufficient historic data to compare alternative fuels and power system subject to ship types, ship size, ship lifecycle, cargo capacity storage, voyage distance. To assess the sustainability of each option, an evaluation criteria system is established, including nine criteria in four aspects (economic, environmental, technological, and social).

Results show that for the old large-size (long-sea shipping) commercial vessels, ensuring sufficient cargo capacity storage is the key concern. Thus, alternative fuels, namely, low-sulfur oil is the most preferable option. For the new large-size vessel, the flexibility of fuel selection is highlighted, thus the dual-fuel engine is a preferable option, particular for the changeover between the LNG and HFO. For short-distance and harbor vessels, electrification offers a promising zero-emission solution, although its adoption depends on the availability of portside infrastructure for charging.

Governments and regulatory bodies play a crucial role in accelerating the adoption of clean technologies through the provision of incentives, such as tax breaks, subsidies, or rebates, to encourage investments in emission abatement technologies. Policies promoting the development of infrastructure for alternative fuels (e.g., LNG bunkering stations and onshore power supply) are instrumental in encouraging stakeholders to adopt cleaner technologies. Furthermore, government support for research and development initiatives aimed at enhancing the efficiency and cost-effectiveness of emerging emission abatement technologies, such as hydrogen fuel cells and ammonia-powered vessels, is essential.

This study also recognizes the variability in regional policies, infrastructure, and economic contexts. For instance, battery-electric-powered transportation is relatively preferable in regions like Singapore, where supportive policies and infrastructure are in place; however, such options may be relatively less preferable in regions like Norway due to differing regional conditions.

5.1. *Policy implication of green transition processes*

Policymakers can apply the study's evaluation framework to design and implement regulations that facilitate the adoption of sustainable maritime technologies. The criteria applied—such as technological maturity, economic feasibility, and environmental impact—can inform policy development, encouraging stakeholders to shift towards environmentally friendly alternatives.

Ports aiming to reduce emissions and promote green shipping initiatives may utilize this framework to assess the feasibility and impact of infrastructure investments. The study's findings on port infrastructure, including the implementation of onshore power supply (OPS) systems and LNG bunkering stations, are applicable to ports worldwide. Moreover, ports across diverse geographic regions with varying environmental regulations and energy resources can adapt the framework to align with local conditions, ensuring that selected abatement measures are both effective and economically viable.

The use of scenario analysis in the study further enhances the transferability of the findings by enabling policymakers to examine how various future scenarios may impact stakeholders' preferences. This approach can be adapted to other sectors or regions to assess how shifts in regulatory environments, market dynamics, or technological advancements could influence the adoption of sustainable solutions.

5.2. *Limitations and future research*

This study faces notable limitations related to behavioral and modeling issues. Regarding behavioral issues, despite employing various strategies—such as learning through modeling, communication through modeling, transparent elicitation methods, learning facilitation skills, and dialogue in modeling—to reduce biases in cognition and judgment, it remains challenging to ensure complete objectivity in stakeholder judgment. As Hämäläinen (2015) suggests, addressing these behavioral issues involves increasing awareness of the social dynamics in model usage, emphasizing systems thinking in problem-solving, and adopting a systems intelligence approach.

Concerning modeling issues, this study does not specify the exact timeline for technology transitions. The AHP-based methods have restrictions on capturing and evaluating time-varying factors (e.g., the lifetime of technology, fuel prices, ship speed, and ship turnaround time). Most importantly, it is not easy to capture available data to measure the lifetime of fuel. Accordingly, it is suggested that future studies should consider adapting the AHP-based method in a way to support decision-making in a dynamic environment.

While this study primarily focuses on specific regions, such as Norway and Singapore, we recognize that various countries worldwide have implemented numerous low-carbon emission reduction policies, such as the Energy Efficiency Design Index (EEDI), Carbon Intensity Indicator (CII), and carbon taxes or emissions trading systems (e.g., EU ETS). The proposed evaluation framework is adaptable and can be applied to other regions with different regulatory landscapes and market conditions. By customizing criteria and weights to align with regional priorities and regulations, this framework can offer valuable insights for decision-makers across diverse maritime contexts. Future research could expand on this work by developing region-specific case studies or cross-sector analyses to further validate and refine the applicability of the framework.

Furthermore, beyond the maritime sector, the evaluation framework could be adapted for other industries facing similar multi-criteria decision-making challenges, including aviation, rail transport, and road logistics. The principles underlying the assessment of technological options based on environmental, economic, and social criteria can facilitate sustainable decision-making across sectors. For example, in aviation, the framework could be employed to assess alternative fuels or propulsion technologies by considering factors such as fuel availability, infrastructure needs, and environmental impact.

Formatting of funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Kaiqi Xu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mario P. Brito:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Patrick Beullens:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the respondent for sharing their relevant experiences and opinions. We would like to thank Mr. Yueqiang Xu who has over 50 years of working experience in ship design and evaluation for numerous in-depth conversations and data.

Data availability

Data will be made available on request.

References

Abadie, L. M., & Goicoechea, N. (2019). Powering newly constructed vessels to comply with ECA regulations under fuel market prices uncertainty: Diesel or dual fuel engine? *Transportation Research Part D: Transport and Environment, 67*, 433–448. https://doi.org/10.1016/J.TRD.2018.12.012

Abadie, L. M., Goicoechea, N., & Galarraga, I. (2017). Adapting the shipping sector to stricter emissions regulations: Fuel switching or installing a scrubber? *Transportation Research Part D: Transport and Environment, 57*, 237–250. https://doi.org/10.1016/J.TRD.2017.09.017

Ahmed, F., & Kilic, K. (2019). Fuzzy analytic hierarchy process: A performance analysis of various algorithms. *Fuzzy Sets and Systems, 362*, 110–128. https://doi.org/10.1016/J.FSS.2018.08.009

Alamoush, A. S., Ballini, F., & Ölçer, A. I. (2020). Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review. *Marine Pollution Bulletin, 160*, Article 111508. https://doi.org/10.1016/J.MARPOLBUL.2020.111508

Alamoush, A. S., Ölçer, A. I., & Ballini, F. (2022). Port greenhouse gas emission reduction: Port and public authorities' implementation schemes. *Research in Transportation Business & Management, 43*, Article 100708. https://doi.org/10.1016/J.RTBM.2021.100708

Alexandridis, G., Kavussanos, M. G., Kim, C. Y., Tsouknidis, D. A., & Visvikis, I. D. (2018). A survey of shipping finance research: Setting the future research agenda. *Transportation Research Part E: Logistics and Transportation Review, 115*, 164–212. https://doi.org/10.1016/J.TRE.2018.04.001

Ammar, N. R. (2019). An environmental and economic analysis of methanol fuel for a cellular container ship. *Transportation Research Part D: Transport and Environment, 69*, 66–76. https://doi.org/10.1016/J.TRD.2019.02.001

Arrow, K. J., & Raynaud, H. (1986). *Social choice and multicriterion decision-making* (p. 1). MIT Press Books.

Asgari, N., Hassani, A., Jones, D., & Nguye, H. H. (2015). Sustainability ranking of the UK major ports: Methodology and case study. *Transportation Research Part E: Logistics and Transportation Review, 78*, 19–39. https://doi.org/10.1016/J.TRE.2015.01.014

Aspen, D. M., & Sparrevik, M. (2020). Evaluating alternative energy carriers in ferry transportation using a stochastic multi-criteria decision analysis approach. *Transportation Research Part D: Transport and Environment, 86*. https://doi.org/10.1016/J.TRD.2020.102383

Bach, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., & Steen, M. (2020). Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. *Transportation Research Part D: Transport and Environment, 87*, Article 102492. https://doi.org/10.1016/J.TRD.2020.102492

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management, 182*, 72–88. https://doi.org/10.1016/J.ENCONMAN.2018.12.080

Bjerkan, K. Y., & Ryghaug, M. (2021). Diverging pathways to port sustainability: How social processes shape and direct transition work. *Technological Forecasting and Social Change, 166*, Article 120595. https://doi.org/10.1016/J.TECHFORE.2021.120595

Bjerkan, K. Y., Ryghaug, M., & Skjølsvold, T. M. (2021). Actors in energy transitions: Transformative potentials at the intersection between Norwegian port and transport systems. *Energy Research & Social Science, 72*, Article 101868. https://doi.org/10.1016/J.ERSS.2020.101868

Bjerkan, K. Y., & Seter, H. (2019). Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports? *Transportation Research Part D: Transport and Environment, 72*, 243–260. https://doi.org/10.1016/J.TRD.2019.05.003

Boele, D. (1998). The "benefits" of a socratic dialogue: Or: Which results can we promise? *Inquiry: Critical Thinking Across the Disciplines, 17*, 48–70. https://doi.org/10.5840/INQUIRYCTNEWS199817335

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D: Transport and Environment, 52*, 408–421. https://doi.org/10.1016/j.trd.2017.03.022

Breyer, C. (2020). *A global overview of future energy, future energy: improved, sustainable and clean options for our planet*. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-102886-5.00034-7

Brynolf, S., Magnusson, M., Fridell, E., & Andersson, K. (2014). Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D: Transport and Environment, 28*, 6–18. https://doi.org/10.1016/J.TRD.2013.12.001

Chu Van, T., Ramirez, J., Rainey, T., Ristovski, Z., & Brown, R. J. (2019). Global impacts of recent IMO regulations on marine fuel oil refining processes and ship emissions. *Transportation Research Part D: Transport and Environment, 70*, 123–134. https://doi.org/10.1016/J.TRD.2019.04.001

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators, 46*, 138–148. https://doi.org/10.1016/J.ECOLIND.2014.06.011

De Brucker, K., MacHaris, C., & Verbeke, A. (2013). Multi-criteria analysis and the resolution of sustainable development dilemmas: A stakeholder management

approach. *European Journal of Operational Research, 224*, 122–131. https://doi.org/10.1016/J.EJOR.2012.02.021
DNV. (2020). *Shipping 2020. høvik*.
Doukas, H., & Nikas, A. (2020). Decision support models in climate policy. *European Journal of Operational Research, 280*, 1–24. https://doi.org/10.1016/J.EJOR.2019.01.017
Duleba, S., & Moslem, S. (2019). Examining Pareto optimality in analytic hierarchy process on real data: An application in public transport service development. *Expert Systems with Applications, 116*, 21–30. https://doi.org/10.1016/J.ESWA.2018.08.049
Escobar, M. T., Aguarón, J., & Moreno-Jiménez, J. M. (2004). A note on AHP group consistency for the row geometric mean priorization procedure. *European Journal of Operational Research, 153*, 318–322. https://doi.org/10.1016/S0377-2217(03)00154-1
Fathi, M., Saray, R. K., & Checkel, M. D. (2011). The influence of Exhaust Gas Recirculation (EGR) on combustion and emissions of n-heptane/natural gas fueled Homogeneous Charge Compression Ignition (HCCI) engines. *Applied Energy, 88*, 4719–4724. https://doi.org/10.1016/J.APENERGY.2011.06.017
Felfernig, A., Falkner, A., & Benavides, D. (2024). *Analysis of feature models* (pp. 45–72). https://doi.org/10.1007/978-3-031-61874-1_3
Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research, 108*, 165–169. https://doi.org/10.1016/S0377-2217(97)00244-0
French, S. (2023). Reflections on 50 years of MCDM: Issues and future research needs. *EURO Journal on Decision Processes, 11*, Article 100030. https://doi.org/10.1016/J.EJDP.2023.100030
Furfari, S., & Mund, E. (2022). Advanced nuclear power for clean maritime propulsion. *The European Physical Journal Plus, 137*, 747. https://doi.org/10.1140/EPJP/S13360-022-02980-5
Gerdsri, N., & Kocaoglu, D. F. (2007). Applying the Analytic Hierarchy Process (AHP) to build a strategic framework for technology roadmapping. *Mathematical and Computer Modelling, 46*, 1071–1080. https://doi.org/10.1016/J.MCM.2007.03.015
Grošelj, P., & Zadnik Stirn, L. (2012). Acceptable consistency of aggregated comparison matrices in analytic hierarchy process. *European Journal of Operational Research, 223*, 417–420. https://doi.org/10.1016/J.EJOR.2012.06.016
Hämäläinen, R. P. (2015). Behavioural issues in environmental modelling – The missing perspective. *Environmental Modelling & Software, 73*, 244–253. https://doi.org/10.1016/J.ENVSOFT.2015.08.019
Hansson, J., Månsson, S., Brynolf, S., & Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass and Bioenergy, 126*, 159–173. https://doi.org/10.1016/J.BIOMBIOE.2019.05.008
Hoong, N. W. (2013). Singapore, the energy economy: From the first refinery to the end of cheap oil, 1960-2010. *Singapore, the Energy Economy: From The First Refinery To The End Of Cheap Oil, 1960-2010*, 1–304. https://doi.org/10.4324/9780203157732/SINGAPORE-ENERGY-ECONOMY-WENG-HOONG-NG
Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment, 409*, 3578–3594. https://doi.org/10.1016/J.SCITOTENV.2011.06.022
Iannaccone, T., Landucci, G., Tugnoli, A., Salzano, E., & Cozzani, V. (2020). Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. *Journal of Cleaner Production, 260*, Article 121069. https://doi.org/10.1016/J.JCLEPRO.2020.121069
IMO. (2013). *Improving the energy efficiency of ships [WWW Document]*. International maritime organization. URL https://www.imo.org/en/OurWork/Environment/Pages/Improvingtheenergyefficiencyofships.aspx (accessed 1.23.24).
IMO. (2020). *IMO 2020:Consistent implementation of MARPOL Annex VI*.
IMO. (2023). *EEXI and CII - ship carbon intensity and rating system [WWW Document]*. International maritime organization. URL https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx (accessed 1.23.24).
Inal, O. B., & Deniz, C. (2020). Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. *Journal of Cleaner Production, 265*, Article 121734. https://doi.org/10.1016/J.JCLEPRO.2020.121734
Jafarzadeh, S., & Schjølberg, I. (2017). Emission reduction in shipping using hydrogen and fuel cells. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE, 10*. https://doi.org/10.1115/OMAE2017-61401
Jafarzadeh, S., & Schjølberg, I. (2018). Operational profiles of ships in Norwegian waters: An activity-based approach to assess the benefits of hybrid and electric propulsion. *Transportation Research Part D: Transport and Environment, 65*, 500–523. https://doi.org/10.1016/J.TRD.2018.09.021
Jiang, L., Kronbak, J., & Christensen, L. P. (2014). The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. *Transportation Research Part D: Transport and Environment, 28*, 19–27. https://doi.org/10.1016/J.TRD.2013.12.005
Karahalios, H. (2017). Evaluating the knowledge of experts in the maritime regulatory field. *Maritime Policy & Management, 44*, 426–441. https://doi.org/10.1080/03088839.2017.1298865
Kavakeb, S., Nguyen, T. T., McGinley, K., Yang, Z., Jenkinson, I., & Murray, R. (2015). Green vehicle technology to enhance the performance of a European port: A simulation model with a cost-benefit approach. *Transportation Research Part C: Emerging Technologies, 60*, 169–188. https://doi.org/10.1016/J.TRC.2015.08.012
Kharub, M., Kattekola, S., & Pendyala, S. K. (2022). 80/20 your organization using AHP for quantitative decision making. *Materials Today Proceedings, 56*, 2437–2442. https://doi.org/10.1016/J.MATPR.2021.08.229
Kim, J., Oh, J., & Lee, H. (2019). Review on battery thermal management system for electric vehicles. *Applied Thermal Engineering, 149*, 192–212. https://doi.org/10.1016/J.APPLTHERMALENG.2018.12.020
Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews, 142*, Article 110861. https://doi.org/10.1016/J.RSER.2021.110861
Krejčí, J., & Stoklasa, J. (2018). Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean. *Expert Systems with Applications, 114*, 97–106. https://doi.org/10.1016/J.ESWA.2018.06.060
Kubler, S., Robert, J., Derigent, W., Voisin, A., & Le Traon, Y. (2016). A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications. *Expert Systems with Applications, 65*, 398–422. https://doi.org/10.1016/J.ESWA.2016.08.064
Lam, J. S. L., Ng, A. K. Y., & Fu, X. (2013). Stakeholder management for establishing sustainable regional port governance. *Research in Transportation Business & Management, 8*, 30–38. https://doi.org/10.1016/J.RTBM.2013.06.001
Li, K., Wu, M., Gu, X., Yuen, K. F., & Xiao, Y. (2020). Determinants of ship operators' options for compliance with IMO 2020. *Transportation Research Part D: Transport and Environment, 86*, Article 102459. https://doi.org/10.1016/J.TRD.2020.102459
Lindstad, E., & Bø, T. I. (2018). Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements. *Transportation Research Part D: Transport and Environment, 63*, 276–290. https://doi.org/10.1016/J.TRD.2018.06.001
Lindstad, H. E., & Eskeland, G. S. (2016). Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny. *Transportation Research Part D: Transport and Environment, 47*, 67–76. https://doi.org/10.1016/J.TRD.2016.05.004
Lindstad, H. E., Rehn, C. F., & Eskeland, G. S. (2017). Sulphur abatement globally in maritime shipping. *Transportation Research Part D: Transport and Environment, 57*, 303–313. https://doi.org/10.1016/J.TRD.2017.09.028
Liu, Y., Eckert, C. M., & Earl, C. (2020). A review of fuzzy AHP methods for decision-making with subjective judgements. *Expert Systems with Applications, 161*, Article 113738. https://doi.org/10.1016/J.ESWA.2020.113738
Lloyd''s Register. (2012). *Your options for emissions compliance. Southampton*.
Lloyd''s Register. (2015). *Understanding technology working together for a safer world your options for emissions compliance guidance for shipowners and operators on the Annex VI SOx and NOx regulations. Southampton*.
Mäkitie, T., Steen, M., Saether, E. A., Bjørgum, Ø., & Poulsen, R. T. (2022). Norwegian ship-owners' adoption of alternative fuels. *Energy Policy, 163*, Article 112869. https://doi.org/10.1016/J.ENPOL.2022.112869
Maleki, H., & Zahir, S. (2013). A comprehensive literature review of the rank reversal phenomenon in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis, 20*, 141–155. https://doi.org/10.1002/MCDA.1479
Mandić, N., Ukić Boljat, H., Kekez, T., & Luttenberger, L. R. (2021). Multicriteria analysis of alternative marine fuels in sustainable coastal marine traffic. *Applied Sciences, 11*. https://doi.org/10.3390/app11062600
Mandić, N., Boljat, H. U., Kekez, T., & Luttenberger, L. R. (2021). Multicriteria analysis of alternative marine fuels in sustainable coastal marine traffic. *Applied Sciences, 11*, 2600. https://doi.org/10.3390/APP11062600
MPA. (2017). *Maritime and port authority of Singapore shipping circular to shipowners*. Singapore: Maritime and Port Authority of Singapore.
MPA. (2022). *Decarbonisation blueprint*. Singapore: Maritime and Port Authority of Singapore.
Ognjanović, I., Gašević, D., & Bagheri, E. (2013). A stratified framework for handling conditional preferences: An extension of the analytic hierarchy process. *Expert Systems with Applications, 40*, 1094–1115. https://doi.org/10.1016/J.ESWA.2012.08.026
Panasiuk, I., & Turkina, L. (2015). The evaluation of investments efficiency of SOx scrubber installation. *Transportation Research Part D: Transport and Environment, 40*, 87–96. https://doi.org/10.1016/J.TRD.2015.08.004
Papamichail, K. N., Alves, G., French, S., Yang, J. B., & Snowdon, R. (2007). Facilitation practices in decision workshops. *Journal of the Operational Research Society, 58*(5), 614–632.
Park, C., Jeong, B., Zhou, P., Jang, H., Kim, S., Jeon, H., … Rashedi, A. (2022). Live-life cycle assessment of the electric propulsion ship using solar PV. *Applied Energy, 309*, Article 118477. https://doi.org/10.1016/J.APENERGY.2021.118477
Parolin, G., McAloone, T. C., & Pigosso, D. C. A. (2024). How can technology assessment tools support sustainable innovation? A systematic literature review and synthesis. *Technovation, 129*, Article 102881. https://doi.org/10.1016/J.TECHNOVATION.2023.102881
Peng, H., An, C., Chen, Z., Tian, X., & Sun, Y. (2023). Promoting cross-regional integration of maritime emission management: A Euro-American linkage of carbon markets. *Environmental Science and Technology, 57*, 12180–12190. https://doi.org/10.1021/ACS.EST.3C02529/ASSET/IMAGES/LARGE/ES3C02529_0005.JPEG
Peng, Y., Zhao, X., Zuo, T., Wang, W., & Song, X. (2021). A systematic literature review on port LNG bunkering station. *Transportation Research Part D: Transport and Environment, 91*, Article 102704. https://doi.org/10.1016/J.TRD.2021.102704
Phillips, L. D., & Phillips, M. C. (1993). Faciliated work groups: Theory and practice. *The Journal of the Operational Research Society, 44*, 533. https://doi.org/10.2307/2584511
Potomkin, M. M., Sedliar, A. A., Deineha, O. V., & Zvarych, A. O. (2021). Comprehensive use of the pareto principle and the analytic hierarchy process to increase the substantiation of alternative ranking results. *Cybernetics and Systems Analysis, 57*, 422–428. https://doi.org/10.1007/S10559-021-00366-6/METRICS
Poulsen, R. T., Ponte, S., & Sornn-Friese, H. (2018). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime

transport. *Geoforum, 89*, 83–95. https://doi.org/10.1016/J.GEOFORUM.2018.01.011
Raharjo, H., Xie, M., & Brombacher, A. C. (2009). On modeling dynamic priorities in the analytic hierarchy process using compositional data analysis. *European Journal of Operational Research, 194*, 834–846. https://doi.org/10.1016/J.EJOR.2008.01.012
Ramanujam, V., & Saaty, T. L. (1981). Technological choice in the less developed countries: An analytic hierarchy approach. *Technological Forecasting and Social Change, 19*, 81–98. https://doi.org/10.1016/0040-1625(81)90050-0
Ren, J., & Lützen, M. (2015). Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties. *Transportation Research Part D: Transport and Environment, 40*, 43–60. https://doi.org/10.1016/J.TRD.2015.07.012
Ren, J., & Lützen, M. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. *Renewable and Sustainable Energy Reviews, 74*, 1003–1019. https://doi.org/10.1016/J.RSER.2017.03.057
Rivarolo, M., Piccardo, S., Montagna, G. N., & Bellotti, D. (2023). A multi-criteria approach for comparing alternative fuels and energy systems onboard ships. *Energy Conversion and Management: X, 20*, Article 100460. https://doi.org/10.1016/J.ECMX.2023.100460
Saaty, R. W. (1987). The analytic hierarchy process—What it is and how it is used. *Mathematical Modelling, 9*, 161–176. https://doi.org/10.1016/0270-0255(87)90473-8
Saaty, T. L. (1980). What is the analytic hierarchy process? *Mathematical Models for Decision Support, 48*, 109–121.
Schinas, O., & Stefanakos, C. N. (2014). Selecting technologies towards compliance with MARPOL Annex VI: The perspective of operators. *Transportation Research Part D: Transport and Environment, 28*, 28–40. https://doi.org/10.1016/j.trd.2013.12.006
Schönsteiner, K., Massier, T., & Hamacher, T. (2016). Sustainable transport by use of alternative marine and aviation fuels—A well-to-tank analysis to assess interactions with Singapore's energy system. *Renewable and Sustainable Energy Reviews, 65*, 853–871. https://doi.org/10.1016/J.RSER.2016.07.027
Sciberras, E. A., Zahawi, B., & Atkinson, D. J. (2017). Reducing shipboard emissions – Assessment of the role of electrical technologies. *Transportation Research Part D: Transport and Environment, 51*, 227–239. https://doi.org/10.1016/J.TRD.2016.10.026
Science and Technology Committee. (2012). *The role of hydrogen in achieving Net Zero*.
Shancita, I., Masjuki, H. H., Kalam, M. A., Fattah, I. M. R., Rashed, M. M., & Rashedul, H. K. (2014). A review on idling reduction strategies to improve fuel economy and reduce exhaust emissions of transport vehicles. *Energy Conversion and Management, 88*, 794–807. https://doi.org/10.1016/J.ENCONMAN.2014.09.036
Shehabuddeen, N., Probert, D., & Phaal, R. (2006). From theory to practice: Challenges in operationalising a technology selection framework. *Technovation, 26*, 324–335. https://doi.org/10.1016/J.TECHNOVATION.2004.10.017
Shen, Y. C., Lin, G. T. R., Li, K. P., & Yuan, B. J. C. (2010). An assessment of exploiting renewable energy sources with concerns of policy and technology. *Energy Policy, 38*, 4604–4616. https://doi.org/10.1016/j.enpol.2010.04.016
Slotte, S., & Hämäläinen, R. P. (2015). Decision structuring dialogue. *EURO Journal on Decision Processes, 3*, 141–159. https://doi.org/10.1007/S40070-014-0028-7
Solvi Hoen, F., Díez-Gutiérrez, M., Babri, S., Hess, S., & Tørset, T. (2023). Charging electric vehicles on long trips and the willingness to pay to reduce waiting for charging. Stated preference survey in Norway. *Transportation Research Part A: Policy and Practice, 175*, Article 103774. https://doi.org/10.1016/J.TRA.2023.103774
Stopford, M. (2010). *Maritime economics*. Routledge. https://doi.org/10.5860/choice.47-3934
Tan, R., Duru, O., & Thepsithar, P. (2020). Assessment of relative fuel cost for dual fuel marine engines along major Asian container shipping routes. *Transportation Research Part E: Logistics and Transportation Review, 140*, Article 102004. https://doi.org/10.1016/J.TRE.2020.102004
Tenold, S. (2019). Norwegian shipping in the 20th century. *Palgrave Studies in Maritime Economics, 327*. https://doi.org/10.1007/978-3-319-95639-8
Tran, T. A., & Daim, T. (2008). A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change, 75*, 1396–1405. https://doi.org/10.1016/J.TECHFORE.2008.04.004
Tseng, P. H., & Pilcher, N. (2019). Evaluating the key factors of green port policies in Taiwan through quantitative and qualitative approaches. *Transport Policy, 82*, 127–137. https://doi.org/10.1016/J.TRANPOL.2018.12.014
Tvedten, I.Ø., & Bauer, S. (2022). Retrofitting towards a greener marine shipping future: Reassembling ship fuels and liquefied natural gas in Norway. *Energy Research & Social Science, 86*, Article 102423. https://doi.org/10.1016/J.ERSS.2021.102423
Vargas, L. G. (1990). An overview of the analytic hierarchy process and its applications. *European Journal of Operational Research, 48*, 2–8. https://doi.org/10.1016/0377-2217(90)90056-H
Velpuri, V. R., Kumari, S., & Muralidharan, K. (2023). Rapid capture of flow carbon dioxide by hard epoxy thermosets with the high glass transition temperature. *Journal of Chemical Sciences, 135*, 1–8. https://doi.org/10.1007/S12039-023-02139-4/FIGURES/5
Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software, 25*, 1268–1281. https://doi.org/10.1016/J.ENVSOFT.2010.03.007
Wan, C., Yan, X., Zhang, D., & Yang, Z. (2019). A novel policy making aid model for the development of LNG fuelled ships. *Transportation Research Part A: Policy and Practice, 119*, 29–44. https://doi.org/10.1016/J.TRA.2018.10.038
Wang, T., Cheng, P., & Zhen, L. (2023). Green development of the maritime industry: Overview, perspectives, and future research opportunities. *Transportation Research Part E: Logistics and Transportation Review, 179*, Article 103322. https://doi.org/10.1016/J.TRE.2023.103322
Wang, Y. M., Luo, Y., & Hua, Z. (2008). On the extent analysis method for fuzzy AHP and its applications. *European Journal of Operational Research, 186*, 735–747. https://doi.org/10.1016/J.EJOR.2007.01.050
Xin, J., Negenborn, R. R., & Lodewijks, G. (2014). Energy-aware control for automated container terminals using integrated flow shop scheduling and optimal control. *Transportation Research Part C: Emerging Technologies, 44*, 214–230. https://doi.org/10.1016/J.TRC.2014.03.014
Xu, Z. (2000). On consistency of the weighted geometric mean complex judgement matrix in AHP. *European Journal of Operational Research, 126*, 683–687. https://doi.org/10.1016/S0377-2217(99)00082-X
Yang, Z. L., Zhang, D., Caglayan, O., Jenkinson, I. D., Bonsall, S., Wang, J., Huang, M., & Yan, X. P. (2012). Selection of techniques for reducing shipping NOx and SOx emissions. *Transportation Research Part D: Transport and Environment, 17*, 478–486. https://doi.org/10.1016/J.TRD.2012.05.010
Yeremenko, K. (2022). International maritime organization and decarbonization of maritime industry: Mandate and instruments. *Lex Portus, 8*, 30–57. https://doi.org/10.26886/2524-101X.8.3.2022.2
Yu, J., Voß, S., & Tang, G. (2019). Strategy development for retrofitting ships for implementing shore side electricity. *Transportation Research Part D: Transport and Environment, 74*, 201–213. https://doi.org/10.1016/J.TRD.2019.08.004
Zhang, X., Bao, Z., & Ge, Y.-E. (2021). Investigating the determinants of shipowners' emission abatement solutions for newbuilding vessels. *Transportation Research Part D: Transport and Environment, 99*, Article 102989. https://doi.org/10.1016/J.TRD.2021.102989
Zhao, J., Wei, Q., Wang, S., & Ren, X. (2021). Progress of ship exhaust gas control technology. *Science of the Total Environment, 799*, Article 149437. https://doi.org/10.1016/J.SCITOTENV.2021.149437
Zhao, X., Ke, Y., Zuo, J., Xiong, W., & Wu, P. (2020). Evaluation of sustainable transport research in 2000–2019. *Journal of Cleaner Production, 256*, Article 120404. https://doi.org/10.1016/J.JCLEPRO.2020.120404
Zhao, Y., Fan, Y., Fagerholt, K., & Zhou, J. (2021). Reducing sulfur and nitrogen emissions in shipping economically. *Transportation Research Part D: Transport and Environment, 90*, Article 102641. https://doi.org/10.1016/J.TRD.2020.102641
Zheng, S., & Chen, S. (2018). Fleet replacement decisions under demand and fuel price uncertainties. *Transportation Research Part D: Transport and Environment, 60*, 153–173. https://doi.org/10.1016/J.TRD.2016.09.001
Zhu, S., Kinnon, M. M., Soukup, J., Paradise, A., Dabdub, D., & Samuelsen, S. (2022). Assessment of the greenhouse gas, episodic air quality and public health benefits of fuel cell electrification of a major port complex. *Atmospheric Environment, 275*, Article 118996. https://doi.org/10.1016/J.ATMOSENV.2022.118996
Zis, T., & Psaraftis, H. N. (2017). The implications of the new Sulphur limits on the European Ro-Ro sector. *Transportation Research Part D: Transport and Environment, 52*, 185–201. https://doi.org/10.1016/j.trd.2017.03.010
Zis, T. P. V. (2019). Prospects of cold ironing as an emissions reduction option. *Transportation Research Part A: Policy and Practice, 119*, 82–95. https://doi.org/10.1016/j.tra.2018.11.003
Zis, T. P. V., & Cullinane, K. (2020). The desulphurisation of shipping: Past, present and the future under a global cap. *Transportation Research Part D: Transport and Environment, 82*, Article 102316. https://doi.org/10.1016/J.TRD.2020.102316