Received 15 January 2024
Revised 8 March 2024
8 April 2024
Accepted 17 April 2024

Evaluation of constraints for investment in NOx emission technologies: case study on Greek bulk carrier owners

Hristos Karahalios
Warsash Maritime School, Solent University, Southampton, UK

Abstract

Purpose – The maritime industry is the transport mode that contributes most to air pollution. The International Maritime Organization (IMO) identified the reduction of air pollution by ships as a crucial issue. Since 1 January 2020, ships have had to adopt strategies and new technologies to eliminate air pollution. However, ship compliance with nitrate oxide (NOx) emission restrictions is more challenging. This paper aims to identify shipowners' challenges in investing in new technologies.

Design/methodology/approach – This paper applied a hybrid methodology combining a survey, a balanced scorecard and fuzzy analytic hierarchy process (F-AHP) to identify and evaluate constraints and weights in investment decision-making for NOx technologies. A survey was carried out to validate constraints.

Findings – A survey was carried out, representing 5.1% of Greek-owned ships by deadweight capacity. The findings provide a weighted list of seven crucial technical and economic constraints faced by ship operators. The constraints vary from ship retrofit expenditure to crew training and waste management. Additionally, NOx emission technologies were compared. It was found that liquefied natural gas is the preferred investment option for the survey participants compared with selective catalytic reduction, exhaust gas recirculation and batteries.

Originality/value – Several studies have dealt with the individual technical feasibility of NOx reduction technologies. However, apart from technical feasibility for a shipowner, the selection of a NOx technology has several managerial and safety risks. Therefore, the originality of this paper is to reveal those constraints that have a higher weight on shipowners. With this cost-benefit approach, investment challenges for ship operators are revealed. Policymakers can benefit from the results of the employed methodology.

Keywords Ship NOx emissions, Maritime regulations, Fuzzy analytic hierarchy process, Balance scorecard, Maritime transportation

Paper type Research paper

1. Introduction

Nitrate oxide (NOx) emission reduction is an essential challenge in all transport sectors (Hwang *et al.*, 2023). The maritime transport sector is argued to contribute most to NOx emissions. The air pollution caused by ships in near-coastal states is claimed to be responsible for health hazards to their citizens since NOx can contribute to photochemical smog and acid rain (Jafarzadeh and Schjølberg, 2018). Several studies have demonstrated that NOx affects mortality (Moreno-Gutiérrez *et al.*, 2019). The cause of maritime air pollution is closely related to engine type and fuel quality. These values are higher at low loads, especially during ship manoeuvring (Tsitsilonis and Theotokatos, 2018).

In 2016, diesel engines were installed in 56% of ships worldwide (Tsitsilonis and Theotokatos, 2018). Ship engines consume 60 million barrels of crude oil, producing 20 million tonnes of NOx, 10 million tonnes of SOx and one million tonnes of particulates (Gabiña *et al.*, 2019). Recent studies estimated that 100,000 ships emit 2.89% of anthropogenic greenhouse gas emissions (Dierickx *et al.*, 2023).

Maritime Business Review
Vol. 9 No. 2, 2024
pp. 160-176
Emerald Publishing Limited
2397-3757
DOI 10.1108/MABR-01-2024-0007

In the aftermath of the Kyoto Protocol, the International Maritime Organization (IMO) has proposed several strategies to minimise air pollution from ships. The IMO has also set a strategy to create a database of emission inventories for further regulations (Roy *et al.*, 2022). As per Annex VI of MARPOL 73/78, a worldwide limit was set for sulphur content in fuels to 0.5% after 1 January 2020, and additional restrictions in some geographical regions were named emission control areas for sulphur (SECA) and NOx (NECA) (Gabiña *et al.*, 2019; Kang *et al.*, 2022). Subject to these regulations, ships are required to be built with stricter emission limits after 1 January 2016, which are defined as "Tier III". The NECAs, which apply to the North American coastal area, are also expected to be designated in the Baltic Sea (Llama and Eriksson, 2019). Furthermore, in 2025, ships must comply with the Required Energy Efficiency Design Index (REEDI) (Kostova *et al.*, 2023).

The focus on NOx emissions specifically is a key contributor to air pollution, including smog formation and acid rain, making it a priority for regulatory intervention. Additionally, reducing NOx emissions aligns with broader environmental goals and commitments from ship operators to combat climate change. Ship operators are required to comply with NOx emission regulations. However, to deal with such an issue, a multicriteria decision approach is required to evaluate the most cost-effective technology. Several challenges include technical, safety and economic issues. In addition, there are some concerns regarding the knowledge required with respect to the dispersion and deposition of ships' air emissions (Claremar *et al.*, 2017). For a ship operator, choosing a new technology may be a multicriteria decision-making problem because of the uncertainty in the shipping industry (Kim and Seo, 2019). The contribution of this paper is to provide a better understanding of why shipowners hesitate to invest in some NOx reduction technologies. The research focuses on the maritime sector because it contributes the largest NOx emissions worldwide. Therefore, this research aims to present a tool capable of evaluating the challenges of available technologies, which is presented in Section 2. Section 3 describes the research methodology to reveal key constraint factors. Utilising experts to validate key constraint factors is presented in Section 4. Finally, a discussion of findings and concluding remarks is presented in Section 5.

2. Literature review on NOx emission technologies

Concerning NOx emission reduction is an essential challenge in all transport sectors (Hwang *et al.*, 2023). European Union studies revealed that 2020 transportation contributed to up to 44% of NOx emissions (Sun *et al.*, 2023). Studies investigating alternatives for NOx elimination have been carried out for road transport (Maurer *et al.*, 2023; Rojas *et al.*, 2023; Szczepański *et al.*, 2023). The maritime sector is the only one that regulates the use of future fuels in geographical emission control regions, aiming for the reduction of NOx (Chorowski *et al.*, 2023). However, the majority of these research studies focus on the technical feasibility of various NOx reduction technologies. On the other hand, in the maritime transport sector, to comply with TIER III IMO emission standards, ship operators must choose to install new technologies or use new types of fuels. In addition, modifications to existing main engines should aim for retarded injection timing to minimise NOx. However, it is complicated to meet TIER III requirements (Czmyr and Kaminski, 2019). More precisely, ship operators must select their strategy to comply with NOx emission regulations until the world fleet complies with IMO Tier III requirements. From the ship operator's viewpoint, compliance with NOx emissions involves a decision problem with several technical alternatives. Most existing studies focus on the costs, benefits and technical challenges of each technology separately. However, for a ship operator, other factors, depending on ship type, size and trading area, affect the choice of technology. Therefore, this study focuses on a comparison of available technologies from a commercial perspective. Therefore, in this section, available technologies are presented.

2.1 Exhaust gas recirculation (EGR) systems

A ship that uses Low Sulphur Fuel Oil (LSFO) needs to adopt additional technologies in order to comply with NOx, as per TIER II. Installing an exhaust gas recirculation (EGR) system is a solution to meet this goal. Llamas and Eriksson (2019) described a method that recirculates exhaust gases into the engine. This technology mitigates ship NOx emissions by recirculating a portion of exhaust gases into the engine's combustion chamber. EGR could effectively meet the IMO Tier III by reducing NOx emissions (Kang *et al.*, 2022). However, some technical concerns are engine thermal efficiency, increased fuel consumption, reforming ratio and methane slip (Qu *et al.*, 2022). Furthermore, EGR controller performance is required when a ship approaches port or manoeuvres during berthing (Llamas and Eriksson, 2019).

2.2 Selective catalytic reduction (SCR) system

Another option for ship operators to achieve a reduction of NOx emissions by up to 90% is the use of a selective catalytic reduction (SCR) system (Ammar and Seddiek, 2017). The SCR systems are believed to be the most suitable technology for marine engines to meet IMO TIER III regulations (Jang *et al.*, 2022). SCR systems typically integrate catalysts into ship exhaust systems with urea injection systems and monitoring equipment to optimise NOx reduction. More advanced solutions are high-pressure systems for marine low-speed engines (Zannis *et al.*, 2022; Zhang *et al.*, 2023). However, an SCR system requires retrofitting an existing ship, and several systems may require urea. A comparison of SCR with EGR indicates that NOx emissions reduction depends on the ship's propulsion system and its main engine specification in various operational conditions (Kostova *et al.*, 2023).

2.3 LNG

An interesting solution to reduce air pollution would be to use other types of fuels. Recent studies favour alternative maritime fuels, such as LNG that drastically reduce NOx emissions (Livaniou *et al.*, 2022). Designing ship fuel powered by LNG main engines appears to be a beneficial proposed solution from environmental, technical and economic viewpoints (Ammar and Seddiek, 2017). When used in marine engines, natural gas has significantly low NOx emissions (Mondejar *et al.*, 2018). It is believed to be the most suitable fuel in environmentally sensitive regions, particularly the Arctic (Katysheva, 2018). However, it is argued that LNG is not the best solution to meet the IMO NOx goals by 2050 as it causes methane slip (Agarwala, 2022). Also, the LNG vessels and their equipment have different power consumption requirements at sea for cargo operations (Martinić-Cezar *et al.*, 2022). Furthermore, ports with gas stations are not available worldwide.

2.4 Biofuels

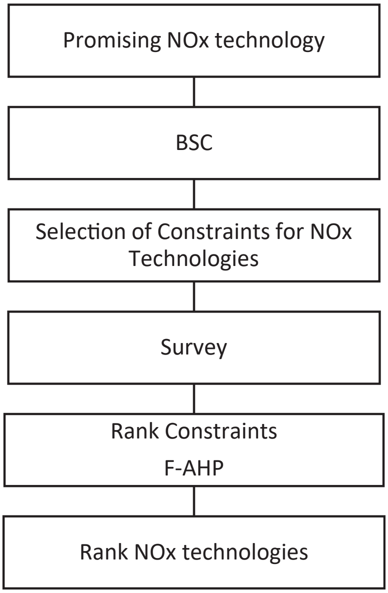
Ship biofuels offer a sustainable alternative for main engine design, utilising renewable sources like algae, vegetable oils or ethanol. Experiments with biofuels have been tested in a large Kamsarmax dry bulk carrier, showing NOx emissions 3% lower than LSMGO (Stathatou *et al.*, 2022). Hydrogen-based biofuels' produce slightly lower climate impacts concerning NOx (Watanabe *et al.*, 2022). Biofuels are sulphur-free and a promising solution to minimise ship air emissions (Issa *et al.*, 2019). Among other benefits, biofuels do not cause oil spills (Balcombe *et al.*, 2019). However, pure biofuels like B100 are costly, so blends are used (Kesieme *et al.*, 2019). From a technical aspect, modifying an existing ship will require compression ignition engines, boilers and gas turbines (Tyrovola *et al.*, 2017). From a maintenance viewpoint, there is limited knowledge of its application to marine engines and crew familiarity. Concerning NOx emissions, biofuels have negative results (Nishio *et al.*, 2018). Better NOx reduction depends on blended biodiesel ratios (Wei *et al.*, 2018). Nevertheless, biofuels are insufficient for NOx reduction without using SCR or EGR (Schröder *et al.*, 2017; Vallapudi *et al.*, 2018; Yasin *et al.*, 2017). In some cases, an increase in PM emissions could be noticed despite EGR installations (Chaichan, 2018). Since biofuels negatively affect the food supply, they will be excluded from the present study (Guven and Kayalica, 2023).

2.5 Batteries

For coastal trade, an option is to use a shore-to-ship power supply at ports with a battery storage system onboard a ship that can save fuel and emissions emitted by the ship. Recent research has revealed that differentiation in awareness and views among shipowners is a significant obstacle to adapting this technology at ports (Kim *et al.*, 2023). When examining the 30-year life cycle environmental performance of lithium-ion batteries, lithium iron phosphate (LFP) and nickel-based Li-ion batteries have shown different results in terms of NOx emissions (Guven and Kayalica, 2023). An alternative to SCR or EGR for ocean voyage ships is using LNG and batteries to reduce the NOx in ship exhausts (Laribi and Guy, 2023; Mondejar *et al.*, 2018). Another option is hydrogen fuel cells hybridised and installed on an exposed deck with batteries that can provide ship power from 1,266 kW to 2,624 kW without emission of NOx (Meca *et al.*, 2022).

3. Research methodology

The proposed methodology aims to evaluate which of the NOx reduction technologies causes fewer constraints and in which a ship operator would prefer to invest. The input of this research is to utilise a hybrid model of fuzzy analytical hierarchy process (F-AHP) to investigate investment constraints with these technologies. It also provided a mechanism to analyse shipowners' most preferred technologies for regulatory compliance. A survey is then used to identify how decision-makers plan to invest. The chosen research methodology, as shown in Figure 1, can be set by using the following steps.



Source(s): Author's own work

Figure 1.
Research methodology

(1) Identify constraints with the means of balanced scorecard (BSC.)

(2) Use of experts to validate constraints

(3) Weighting and validating constraints with fuzzy-AHP

(4) Conduct a survey in Greek industry

(5) Prioritise existing technologies

3.1 Selected constraints for NOx technologies

After identifying the available NOx technologies, the next step is to identify option's associated constraints. The main benefit is compliance with maritime regulations. On the other hand, burdens may be more complex than financial costs. Nevertheless, despite the sophisticated design of these technologies, more research is needed on their impact on customer satisfaction from a ship management viewpoint. This research aims to fill this gap by exploring the current NOx ship technologies and their impact on businesses operating in the industry.

Several cost-benefit applications in the literature could fit the purpose of this research. However, adopting the BSC is the most appropriate since it includes noneconomic burdens such as internal processes and training. In the traditional approach of BSC, a cost-benefit analysis evaluates impacts on financial, customer satisfaction, internal business and learning and growth perspectives (Samasm *et al.*, 2018). The generated scorecard, with fewer than 20 measures, is suitable for a specific problem and is used as a reference to all management levels (Dinçer *et al.*, 2019; Malagueño *et al.*, 2018; Muda *et al.*, 2018). In the literature, several BSC applications are dealing with various maritime challenges (Lin *et al.*, 2022; Maydanova *et al.*, 2019; Šaković Jovanović *et al.*, 2019; Sanchez-Gonzalez *et al.*, 2022).

3.2 Constraints selection using literature review

There is sufficient literature about the costs and benefits of technologies used to minimise NOx emissions from marine engines. Including studies showing techno-economical and operational challenges with equipment used to eliminate SOx emissions from ships is also crucial. By applying BSC, selected studies can be used to identify constraints faced by ship operators when selecting an air pollution technology. During the survey, the participants can verify their validity or suggest new ones.

Therefore, some common issues under each BSC perspective should be used to identify similar problems with NOx technologies suitable for TIER III. Following the BSC approach, financial perspective measures are needed to determine if the adoption of NOx technology could be proven cost-effective. Ship operators are hesitant to invest in new technologies due to the limitations of their economic efficiency (Livaniou *et al.*, 2022; Thalis and Psaraftis, 2018). Examples of ship operation costs are energy consumption, with higher fuel consumption being the most crucial (Abadie *et al.*, 2017; Ammar and Seddiek, 2017). Essential constraints for selection of compliance technology include bunker prices, ship engine type and vessel operating profile (Thalis and Psaraftis, 2018). However, some generic challenges appear to be high costs for installation, retrofitting and stability (Başhan *et al.*, 2022). Fuel tank capacity for new types of fuels is a crucial issue since it may need modifications (Lee *et al.*, 2021).

From the viewpoint of customer satisfaction, any operator needs their ship to avoid restrictions from a trading area such as NOx SECA. Minimising fuel consumption in terms of prices is also essential (Abadie *et al.*, 2017; Kostova *et al.*, 2023). In order to maximise the commercial efficiency of a ship, it should be able to access SECA ports irrespective of fuel consumption (Gu and Wallace, 2017; Sirviö, 2018). On the other hand, higher fuel consumption from new onboard devices should be avoided (Qu *et al.*, 2022). Similarly, electrical power consumption should be a technical barrier, although sometimes unavoidable.

From an internal business perspective, there are several technical challenges. Installation of new equipment on a ship requires extensive studies to determine possible failures on the ship hull or power failures (Geertsma *et al.*, 2017). The disposal of chemicals required is a primary concern, as shown in the use of scrubbers (Abadie *et al.*, 2017; Claremar *et al.*, 2017; Jiang and Hansen, 2016; Tran, 2017). Therefore, waste management has been identified as a top priority (Başhan *et al.*, 2022; Gupta *et al.*, 2018; Mir *et al.*, 2016).

Concerning the learn and growth perspective, any ship modifications require seafarers to be trained for ship-specific actions, including fuel switchover, bunker scenarios, charterers' requirements and crew training (Laribi and Guy, 2023; Wang *et al.*, 2018). The existing legislation concerning scrubber systems will be revised as more knowledge will be gained from actual operation (Sofiev *et al.*, 2018). A summary of the proposed technical constraints, as identified in the literature, is shown in Table 1.

3.3 Prioritisation of constraints with F-AHP

Some research suggests that a BSC scorecard could be used to shape a hierarchical scorecard since the contribution of each perspective may not be equal to others (Albooyeh and Yaghmaie, 2019). The constraint factors identified in Section 2.2 may not have equal weighting, and therefore, the F-AHP is employed to determine their significance. Employing F-AHP is a structured approach that enhances the robustness of analysing shipowners' challenges in investing in new technologies for reducing NOx emissions and offers numerous benefits. The F-AHP is capable of dealing with uncertainty and vagueness in human decisions to a greater extent than classical AHP (Thengane *et al.*, 2014). Therefore, in this study, F-AHP facilitates the prioritisation of constraints, aiding shipowners in focusing on the most critical issues in their investment decisions. Measuring the constraints's weight can be applied with F-AHP (Ak and Gul, 2019; Venkatesh *et al.*, 2019; Zhang and Lam, 2019). The selection of the F-AHP tool is beneficial because it can be applied to a spreadsheet. AHP's simplicity is why it has been established as a comprehensive decision-making tool (Kashav *et al.*, 2022; Kyriakidis *et al.*, 2018). F-AHP is not time-consuming and can generate weights and ranking orders in the dataset (Nazim *et al.*, 2022).

Perspective	Criteria	Reference
Economical	Price of fuel	Abadie *et al.* (2017) Thalis and Psaraftis (2018) Kostova *et al.* (2023)
Economical	Installation cost	Geertsma *et al.* (2017) Başhan *et al.* (2022)
Economical	Fuel tanks capacity	Lee *et al.* (2021)
Customer satisfaction	Higher fuel consumption	Abadie *et al.* (2017) Ammar and Seddiek (2017) Qu *et al.* (2022)
Customer satisfaction	Power consumption	Kumar *et al.* (2019) Meca *et al.* (2022)
Internal business	Waste management	Gupta *et al.* (2018) Mir *et al.* (2016) Başhan *et al.* (2022)
Learn and growth	Crew training	Wang *et al.* (2018) Laribi and Guy (2023)

Source(s): Author's own work

Table 1. Proposed technical constraints

Concerning the maritime industry, there are several research studies applying F-AHP. For instance, fuzzy multi-attribute decision-making methods have been used to assess scrubber systems' health, safety and environmental aspects (Başhan *et al.*, 2022). Barriers in maritime supply chains demonstrated fuzzy logic's role in managing complexities (Kashav *et al.*, 2022). F-AHP combined with the VIKOR method was used to evaluate Industry 4.0's impact on the maritime sector (Mollaoglu *et al.*, 2022). Other F-AHP applications are shown in ship acquisition issues (Park *et al.*, 2018). Finally, F-AHP has been used in big data analytics in maritime organisations (Zhang and Lam, 2019). For data collection, linguist terms, as shown in Table 2, were applied. Using linguistic terms in decision-making is widespread (Mollaoglu *et al.*, 2022).

Following the F-AHP process, it is possible to design a hierarchical structure where each hierarchy node is compared for its significance with the other nodes (Kokangül *et al.*, 2017). For example, in a matrix denoted as A, the weight of each criterion a_{ij} $(i,j = 1,2,3, \ldots n)$ is evaluated by multiple pairwise comparisons. The linguistic scale for each a_{ij} shows the importance of ai over a_j where aji = 1/aij adopts the principal eigenvalue (Park *et al.*, 2018; Peña *et al.*, 2019). Then, an estimation of the eigenvector is calculated as in Eq. (1). F-AHP calculations can be used for further analysis of each respondent or group (Sakhardande and Gaonkar, 2022). Therefore, it is easier to examine different groups and the consistency of their answers with the consistency index (*CI*), as shown in Eq. (2) (Qu *et al.*, 2018). The consistency ratio (*CR*) of a matrix can be calculated by dividing *CI* by the expected random index (RI) pre-set values (Liu *et al.*, 2020). For better evaluation of F-AHP results, the linguistic variables should become crisp numbers (M_{crisp}) (Awan *et al.*, 2022). For the fuzzy triangular numbers used hereunder, this conversion can be achieved by using Eq. (3), where c denotes the highest value (Irvanizam *et al.*, 2018).

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

$$M_{crisp} = a + \frac{(c - b)}{4} \tag{3}$$

3.4 Survey design

3.4.1 Survey design, sampling and data collection. The study aims to explore ship management companies' willingness and confidence level to invest in new technologies that will minimise NOx air emissions caused by their ships. Based on the literature, the combination of regulatory trends and the availability of NOx minimisation technologies should meet ship managers' demand for these technologies in the maritime industry. To fulfil the research

Table 2.
Linguistic scale

Linguistic scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equal importance	(1,1,1)	(1,1,1)
Weakly more important	(1,3/2,2)	(1/2,2/3,1)
Strongly more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more important	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

Source(s): Author's own work

aims, a survey is required in this study. The survey's main point is to identify the most promising technology for NOx reduction in which they would invest. The sampling plan is for companies managing ships located in Greece. A review of the Shipping Intelligence database (Clarksons.net, 2022) reveals that Greek shipowners invested in technologies such as LNG, SOx scrubber, eco-electronic engines and biofuel. Table 3 shows technologies until July 2022 of 4,615 with deadweight (DWT) larger than 10,000 tonnes. Smaller ships were excluded from this study as they are more likely to be involved in coastal trade at specific ports. Therefore, Greek shipowners should prioritise these technologies in this survey based on their preferences.

The survey was carried out by distributing questionnaires directly to ship management companies based in Greece. The companies were selected from a list of contacts published by the Skolarikos Maritime Database (Skolarikos Maritime Bureau, 2022). This approach aimed to reach most ship management companies involved in worldwide trade, regardless of fleet size, type and flag. The mode of delivery was an online survey where respondents could provide their answers at their convenience. Then, a web-based database was created that was useful for analysis. To administer the survey, the author distributed the questionnaires by sending out invitations to participate via email to ship management companies on the list. Participants were answered using linguistic terms. Also, confidentiality was ensured; however, the authors can provide replies.

The survey consists of three sections. The introductory section describes the objectives of the study. It should be highlighted that this study seeks to prioritise the reasons behind invention constraints for new NOx technologies. The second section includes questions regarding the demographics of respondents and their companies. The third section was for respondents to rank their constraints. With this section, it is possible to validate the indicators identified in the literature review. Of course, the responders need to be qualified as experts. When dealing with maritime cases, essential formal qualifications for an expert should include an MSC degree, several years of managerial experience in ship operations, and a background as an academic or seafarer (Karahalios, 2021). The fourth section has two questions. The first was to rate the most promising technology for NOx reduction. This second question is about a strategy to comply with existing SOx requirements that have already been enforced. With this approach, a more holistic idea of investing in dealing with shipboard air emissions is a more holistic approach.

4. Survey data analysis

The replied companies have a cumulative fleet of 245 ships with a total capacity of 14,250,000 DWT. Data collection was carried out in May and June 2022. As per the UNCTAD report (2022), Greek ownership is 17.63% of the global fleet in deadweight ton (DWT) terms, with more than 350 m DWT. In this survey, 14,562,000 DWT represented 4% of that fleet or 5.1%

NOx technologies	Ships
Eco-electronic engine modern	1,099
LNG capable	129
SOx scrubber status	817
LNG ready	18
Biofuel	3
Eco-electronic engine	0
Alternative fuel types	0

Source(s): Author's own work

Table 3. Distribution of NOx technologies Greek-owned ships until July 2022

of Greek-owned ships. As shown in Table 4, the respondents who participated were in the same age group and had high academic and industrial qualifications. They were also the decision-makers for investing in new technologies with NOx issues.

Each expert had to make a pairwise comparison for each constraint using the linguistic terms in Table 2. For example, as shown in Table 5, each expert compared the importance of fuel price with the installation cost. The chosen linguistic terms are shown in the first column. The average of linguist terms for this pairwise comparison is found to be (0.77, 0.90 and 1.10). The corresponding crisp numbers using Equation (3) are shown in the second column. The crisp calculated value is equal to 0.819, and this value is transferred into the matrix shown in Table 6. With this approach, it was possible to have a pairwise comparison matrix with crisp

Table 4.
Responders' qualifications

Academic qualification	Position	Years of managerial experience
Ph.D.	Safety Management	More than 10
M.Sc	Technical Management	More than 10
M.Sc	Technical Management	Between 6 and 10
M.Sc	Safety Inspection/Audit/Accident Investigation	Less than 5
M.Sc	Technical Management	More than 10
B.Sc	Technical Management	More than 10
M.Sc	Technical Management	More than 10

Source(s): Author's own work

Table 5.
Example of experts' judgements for price of fuel vs installation cost

Experts	Linguist triangular number	Crisp number
Expert 1	(1,3/2,2)	1.125
Expert 2	(1,1,1)	1
Expert 3	(2/5,1/2,2/3)	0.44
Expert 4	(1,1,1)	1
Expert 5	(1/2,2/3,1)	0.583
Expert 6	(1/2,2/3,1)	0.583
Expert 7	(1,1,1)	1
Average	*(0.77,0.90,1.10)*	*0.819*

Source(s): Author's own work

Table 6.
Crisp matrix

	Price of fuel	Higher fuel consumption	Installation cost	Tanks capacity	Power consumption	Waste management	Crew training
Price of fuel	1.000	1.043	0.819	1.091	1.263	1.263	1.000
Higher fuel consumption	0.958	1.000	0.852	1.045	1.211	1.211	0.958
Installation cost	1.062	1.174	1.000	1.227	1.421	1.421	1.125
Tanks capacity	0.917	0.957	0.815	1.000	1.158	1.158	0.917
Power consumption	0.792	0.826	0.704	0.864	1.000	1.000	0.792
Waste management	0.792	0.826	0.704	0.864	1.000	1.000	0.792
Crew training	1.000	1.043	0.889	1.091	1.263	1.263	1.000

Source(s): Author's own work

numbers. The matrix in Table 6 represents the average crisp values of all experts' judgements. Therefore, any *CI* value calculated using Equation (2) represents the consistency of all participants. The *CI* of the matrix was found to be 0.011, which shows consistency in experts' judgements.

The constraints were weighed with operations, as shown in Section 3.1 and presented in Table 7. Based on these findings, it appears that the most critical constraints in investing are the installation cost and the price of fuel. Crew training and higher fuel consumption ranked third and fourth, respectively, followed by fuel tank capacity. Eventually, power consumption and waste management are ranked in the last positions with similar weights. It is notable that although there are different priorities, the weight differences among constraints are very close, and it is expected that companies with different commercial priorities may have different decisions.

By further examining the survey data, four different groups can be distinguished based on the SOx strategy they followed considering the size of ships and managed fleet volume, as shown in Table 8. LSFO is the most favourable option for companies with ships less than 36,000dwt. However, only Group 1 appears to use LSMGO as well. Groups 3 and 4 are ships that are managed by larger companies; LSMGO was used only. Also, the scrubber is fitted on Group 3 ships larger than 80,000 DWT. Interestingly, when examining replies with SOx, most ships did not invest in technology.

Therefore, it was necessary to examine how each group prioritised constraints and how they would prefer to use NOx technology. By carrying F-AHP within the groups of decision-makers, the priorities are different, as shown in Table 9. For Group 1, the price of fuels and crew training is the highest ranking, while for Group 2, installation cost and fuel tank capacity are the highest. For companies in Group 3, installation cost is prioritised. Eventually, Group 4 provided higher weight to fuel consumption, but many constraints related to higher fuel consumption, installation costs and crew training.

Constraint	Ranking
Installation cost	0.1608
Price of fuel	0.1521
Crew training	0.1457
Higher fuel consumption	0.1406
Fuel tanks capacity	0.1381
Power consumption	0.1259
Waste management	0.1251

Source(s): Author's own work

Table 7.
Ranking of constraints

Groups	Fleet percentage	Fleet size	Ship size	LSFO	LSMGO	Scrubbers fitted
Group 1	0.113	3–24	Less than 36,000 DWT	YES	YES	
Group 2	0.063	5–10	Less than 36,000 DWT	YES	NO	
Group 3	0.588	>130	Between 36, 000 and 80,000 DWT	NO	YES	
Group 4	0.238	>50	More than 80,000 DWT	NO	YES	Open Loop

Source(s): Author's own work

Table 8.
Comparison of groups with SOx strategy

As there are different priorities, the survey outcome was that there were differences between groups in the ranking of NOx technologies. Table 10 shows the results of the survey with respect to NOx preference. Overall, respondents show a preference for SCR, followed by the LNG. Eventually, EGR and batteries are ranked in the third and fourth positions, respectively. However, when examining each group, it is noticed that LNG is the first option in 3 out of 4 groups.

5. Discussion and conclusions

From a practical viewpoint, this paper enables ship operators to evaluate the costs and benefits of selecting a new NOx technology. The constraints for determining the value of each technology revealed in the literature were seven. Those can be adopted in similar studies and used by any ship operator. The benefit to a ship operator is to use the revealed weighted constraints as part of a cost-effective methodology for selecting optimal NOx emission technology. Nevertheless, ship operators can comply with environmental regulations without reducing their fleet trading options.

The constraints weights show a significant advantage over technologies that use less costly fuels, which could determine future ship design. The commercial advantage depends on higher fuel consumption. Installation and maintenance practical challenges are also found significant. The ranking of alternatives indicates that the use of LNG is a positive choice due to its environmental benefits. In contrast, exhaust gas recirculation and batteries are ranked last.

From a regulatory perspective, it is supported in this paper that investment in new technologies on existing ships is challenging. Ship operators face practical and costly implications from new technologies with uncertain results. The maritime industry may invest in environmental technologies when this can minimise commercial risks such as bunker price and ship speed maintenance as constraints. The study was limited to bulk carriers. However, it should be tested on larger ships or different types.

The survey results can be useful for future studies on air emission technologies. It can be used by manufacturers and policymakers when considering stakeholders' constraints,

	Group 1	Group 2	Group 3	Group 4
Price of fuel	0.164	0.125	0.148	0.205
Higher fuel consumption	0.145	0.125	0.148	0.159
Installation cost	0.145	0.188	0.185	0.159
Fuel tanks capacity	0.127	0.188	0.130	0.114
Overconsumption	0.127	0.125	0.111	0.114
Waste management	0.127	0.125	0.130	0.091
Crew training	0.164	0.125	0.148	0.159

Source(s): Author's own work

Table 9.
Ranking of constraints of each group

	Group 1	Group 2	Group 3	Group 4	All groups
LNG	0.264	0.223	0.261	0.246	0.261
EGR	0.198	0.260	0.178	0.185	0.178
SCR	0.198	0.186	0.181	0.246	0.181
BATTERIES	0.139	0.130	0.181	0.123	0.180

Source(s): Author's own work

Table 10.
Ranking of NOx technologies

particularly shipowners. The contribution of this study is that it reveals the cost and noneconomic constraints that ship operators will face in compliance with NOx emission TIER III requirements. The data show that the bunker price of fuels, higher fuel consumption, installation cost and fuel tank capacity are essential constraints for decision-makers investing in new technologies. Experts concluded that the factors ranked highest included crew training and waste management, apart from installation costs. This is a reasonable outcome after scrubbing challenges. It is worth investigating if the same applies to other countries with different ship management cultures.

BSC has proven useful in developing a cost-benefit analysis framework. The F-AHP appears to have a significant contribution as a decision-making model. The ranking of available alternatives could be evaluated with acceptable constraints. The strength of F-AHP was found to be beneficial when validating the model and expertise of participants. A robust model is presented, which could be easily applied in a spreadsheet. Furthermore, the F-AHP methodology can be used with different constraints in case a ship operator chooses a different way. However, such differences in selected constraints will not affect the model's validity.

Regarding future research in this area, conducting a survey similar to other parts of transport modes and other types of ships is recommended. This paper contributes to the already-existing literature by arguing that the maritime industry has to face several challenges with NOx emissions. The choice of a system may need to be revised or a long-term solution may be needed. The IMO goals and deadlines should be harmonised with the feasibility of exploring new solutions in the existing world fleet. On the other hand, the variation of systems may need to be more consistent within the industry, especially for waste management and maintenance challenges.

References

Abadie, L.M., Goicoechea, N. and Galarraga, I. (2017), "Adapting the shipping sector to stricter emissions regulations: fuel switching or installing a scrubber?", *Transportation Research D: Transport and Environment*, Vol. 57, pp. 237-250, doi: 10.1016/j.trd.2017.09.017.

Agarwala, N. (2022), "Is LNG the solution for decarbonised shipping?", *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, Vol. 6 No. 4, pp. 158-166, doi: 10.1080/25725084.2022.2142428.

Ak, M.F. and Gul, M. (2019), "AHP–TOPSIS integration extended with Pythagorean fuzzy sets for information security risk analysis", *Complex and Intelligent Systems*, Vol. 5 No. 2, pp. 113-126, doi: 10.1007/s40747-018-0087-7.

Albooyeh, S. and Yaghmaie, F. (2019), "Evaluation of knowledge management model in construction companies using the fuzzy AHP and fuzzy TOPSIS", *International Journal of Business Excellence*, Vol. 18 No. 1, pp. 64-97, doi: 10.1504/ijbex.2019.10020907.

Ammar, N.R. and Seddiek, I.S. (2017), "Eco-environmental analysis of ship emission control methods: case study RO-RO cargo vessel", *Ocean Engineering*, Vol. 137, pp. 166-173, doi: 10.1016/j.oceaneng.2017.03.052.

Awan, U., Hannola, L., Tandon, A., Goyal, R.K. and Dhir, A. (2022), "Quantum computing challenges in the software industry. A fuzzy AHP-based approach", *Information and Software Technology*, Vol. 147, 106896, doi: 10.1016/j.infsof.2022.106896.

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A. and Staffell, I. (2019), "How to decarbonise international shipping: options for fuels, technologies and policies", *Energy Conversion and Management*, Vol. 182, pp. 72-88, doi: 10.1016/j.enconman.2018.12.080.

Başhan, V., Yucesan, M., Demirel, H. and Gul, M. (2022), "Health, safety, and environmental failure evaluation by hybridising fuzzy multi-attribute decision-making methods for maritime scrubber systems", *Environmental Monitoring and Assessment*, Vol. 194 No. 9, p. 641, doi: 10.1007/s10661-022-10284-5.

Chaichan, M.T. (2018), “Performance and emission characteristics of C.I.E. using hydrogen, biodiesel, and massive EGR”, *International Journal of Hydrogen Energy*, Vol. 43 No. 10, pp. 5415-5435, doi: 10.1016/j.ijhydene.2017.09.072.

Chorowski, M., Lepszy, M., Machaj, K., Malecha, Z., Porwisiak, D., Porwisiak, P., Rogala, Z. and Stanclik, M. (2023), “Challenges of application of green ammonia as fuel in onshore transportation”, *Energies*, Vol. 16 No. 13, p. 4898, doi: 10.3390/en16134898.

Claremar, B., Rutgersson, A. and Haglund, K. (2017), “Ship emissions and the use of current air cleaning technology: contributions to air pollution and acidification in the Baltic Sea”, *Earth System Dynamics*, Vol. 8 No. 4, pp. 901-919, doi: 10.5194/esd-8-901-2017.

Clarksons.net (2022), *Clarksons Shipping Intelligence Network* (accessed 26 July 2022).

Czmyr, S. and Kaminski, P. (2019), “Comparison of reduction systems of harmful substances into the atmosphere in accordance to requirements of I.M.O. Tier III”, *Journal of KONES*, Vol. 26 No. 3, pp. 7-14.

Dierickx, J., Dejaegere, Q., Peeters, J., Sileghem, L. and Verhelst, S. (2023), “Performance and emissions of a high-speed marine dual-fuel engine operating with methanol-water blends as a fuel”, *Fuel*, Vol. 333, 126349, doi: 10.1016/j.fuel.2022.126349.

Dinçer, H., Yüksel, S. and Martinez, L. (2019), “Balanced scorecard-based analysis about European energy investment policies: a hybrid hesitant fuzzy decision-making approach with quality function deployment”, *Expert Systems With Applications*, Vol. 115, pp. 152-171, doi: 10.1016/j.eswa.2018.07.072.

Gabiña, G., Martin, L., Basurko, O.C., Clemente, M., Aldekoa, S. and Uriondo, Z. (2019), “Performance of marine diesel engine in propulsion mode with a waste oil-based alternative fuel”, *Fuel*, Vol. 235, pp. 259-268, doi: 10.1016/j.fuel.2018.07.113.

Geertsma, R.D., Negenborn, R.R., Visser, K.H. and J.J. (2017), “Design and control of hybrid power and propulsion systems for smart ships: a review of developments”, *Applied Energy*, Vol. 194, pp. 30-54, doi: 10.1016/j.apenergy.2017.02.060.

Gu, Y. and Wallace, S.W. (2017), “Scrubber: a potentially overestimated compliance method for the Emission Control Areas: the importance of involving a ship’s sailing pattern in the evaluation”, translated by D, R.P. and Envi.

Gupta, H. (2018), “Assessing organisations performance on the basis of G.H.R.M. practices using B.W.M. and fuzzy T.O.P.S.I.S”, *Journal of Environmental Management*, Vol. 226, pp. 201-216, doi: 10.1016/j.jenvman.2018.08.005.

Guven, D. and Kayalica, M.O. (2023), “Life-cycle assessment and life-cycle cost assessment of lithium-ion batteries for passenger ferry”, *Transportation Research Part D: Transport and Environment*, Vol. 115, 103586, doi: 10.1016/j.trd.2022.103586.

Hwang, J., Maharjan, K. and Cho, H. (2023), “A review of hydrogen utilisation in power generation and transportation sectors: achievements and future challenges”, *International Journal of Hydrogen Energy*, Vol. 48 No. 74, pp. 28629-28648, S0360319923017123, doi: 10.1016/j.ijhydene.2023.04.024.

Irvanizam, I., Rusdiana, S., Amrusi, A., Arifah, P. and Usman, T. (2018), “An application of fuzzy multiple-attribute decision making model based on simple additive weighting with triangular fuzzy numbers to distribute the decent homes for impoverished families”, *Journal of Physics: Conference Series*, Vol. 1116 No. 2, pp. 022016-022021, doi: 10.1088/1742-6596/1116/2/022016.

Issa, M., Ibrahim, H., Ilinca, A. and Hayyani, M.Y. (2019), “A review and economic analysis of different emission reduction techniques for marine diesel engines”, *Open Journal of Marine Science*, Vol. 9 No. 03, pp. 148-171, doi: 10.4236/ojms.2019.93012.

Jafarzadeh, S. and 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*, Vol. 65, pp. 500-523, translated by D, R.P. and Envi., doi: 10.1016/j.trd.2018.09.021.

Jang, J., Ahn, S., Na, S., Koo, J., Roh, H. and Choi, G. (2022), "Effect of a plasma burner on NOx reduction and catalyst regeneration in a marine S.C.R. System", *Energies*, Vol. 15 No. 12, p. 4306, doi: 10.3390/en15124306.

Jiang, L. and Hansen, C.Ø. (2016), "Investing in marine scrubber under uncertainty with real option thinking", *The Annual Conference of the International Association of Maritime Economists. I.A.M.E. 2016*.

Kang, M.K., Min, K.Y., Park, S.U. and Choi, J.D. (2022), "An experimental study on the air pollutant emission characteristics of high-speed diesel engine for small coastal ships according to the application of the LP EGR and DOC-DPF systems", *Journal of Advanced Marine Engineering and Technology*, Vol. 46 No. 1, pp. 1-8, doi: 10.5916/jamet.2022.46.1.1.

Karahalios, H. (2021), "Application of AHP-TOPSIS for knowledge evaluation of ship operators", *International Journal of Business Excellence*, Vol. 24 No. 4, pp. 437-459, doi: 10.1504/IJBEX.2021.117652.

Kashav, V., Garg, C.P., Kumar, R. and Sharma, A. (2022), "Management and analysis of barriers in the maritime supply chains (M.S.Cs) of containerised freight under fuzzy environment", *Research in Transportation Business and Management*, Vol. 43, 100793, doi: 10.1016/j.rtbm.2022.100793.

Katysheva, E.G. (2018), "The role of the Northern Sea route in Russian L.N.G. Projects development", *IOP Conference Series: Earth and Environmental Science*, Vol. 180 No. 1, pp. 12008-120013.

Kesieme, U., Pazouki, K., Murphy, A. and Chrysanthou, A. (2019), "Attributional life cycle assessment of biofuels for shipping: addressing alternative geographical locations and cultivation systems", *Journal of Environmental Management*, Vol. 235, pp. 96-104, doi: 10.1016/j.jenvman.2019.01.036.

Kim, A.-R. and Seo, Y.-J. (2019), "The reduction of SOx emissions in the shipping industry: the case of Korean companies", *Marine Policy*, Vol. 100, pp. 98-106, doi: 10.1016/j.marpol.2018.11.024.

Kim, A.-R., Seo, J. and Seo, Y.-J. (2023), "Key barriers to adopting onshore power supply to reduce port air pollution: policy implications for the maritime industry in South Korea", *Marine Policy*, Vol. 157, 105866, doi: 10.1016/j.marpol.2023.105866.

Kokangül, A., Polat, U. and Dağsuyu, C. (2017), "A new approximation for risk assessment using the AHP. and Fine Kinney methodologies", *Safety Science*, Vol. 91, pp. 24-32, doi: 10.1016/j.ssci.2016.07.015.

Kostova, I., Nikiforov, V., Pirovsky, C. and Ilieva, G. (2023), "NOx reduction system selection and energy efficiency impact evaluation for ships sailing in restricted areas", *IOP Conference Series: Earth and Environmental Science*, No. 1, 012026, doi: 10.1088/1755-1315/1128/1/012026.

Kumar, J., Kumpulainen, L. and Kauhaniemi, K. (2019), "Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions", *International Journal of Electrical Power & Energy Systems*, Vol. 104, pp. 840-852.

Kyriakidis, M., Majumdar, A. and Ochieng, W.Y. (2018), "The human performance railway operational index-a novel approach to assess human performance for railway operations", *Reliability Engineering and System Safety*, Vol. 170, pp. 226-243, doi: 10.1016/j.ress.2017.10.012.

Laribi, S. and Guy, E. (2023), "Marine energy transition with L.N.G. and electric batteries: a technological adoption analysis of Norwegian ferries", *Maritime Business Review*, Vol. 8 No. 1, pp. 80-96, doi: 10.1108/mabr-11-2021-0086.

Lee, Y.G., Kim, J.K. and Lee, C.H. (2021), "Analytic hierarchy process analysis for industrial application of L.N.G. bunkering: a comparison of Japan and South Korea", *Energies*, Vol. 14 No. 10, p. 2965, doi: 10.3390/en14102965.

Lin, W.C. (2022), "Maritime environment assessment and management using through balanced scorecard by using D.E.M.A.$^{\mathrm{TEL}}$ and A.N.P. technique", *International Journal of Environmental Research and Public Health*, Vol. 19 No. 5, p. 2873, doi: 10.3390/ijerph19052873.

Liu, Y., Eckert, C. M. and Earl, C. (2020), "A review of fuzzy AHP methods for decision-making with subjective judgements", *Expert systems with applications*, Vol. 161, 113738.

Livaniou, S., Chatzistelios, G., Lyridis, D.V. and Bellos, E. (2022), "L.N.G. vs M.D.O. in marine fuel emissions tracking", *Sustainability*, Vol. 14 No. 7, p. 3860, doi: 10.3390/su14073860.

Llamas, X. and Eriksson, L. (2019), "Control-oriented modeling of two-stroke diesel engines with exhaust gas recirculation for marine applications", *Proceedings of the Institution of Mechanical Engineers, M: Journal of Engineering for the Maritime Environment*, Vol. 233 No. 2, pp. 551-574, doi: 10.1177/1475090218768992.

Malagueño, R., Lopez-Valeiras, E. and Gomez-Conde, J. (2018), "Balanced scorecard in S.M.E.s: effects on innovation and financial performance", *Small Business Economics*, Vol. 51 No. 1, pp. 221-244, doi: 10.1007/s11187-017-9921-3.

Martinić-Cezar, S., Bratić, K., Jurić, Z. and Račić, N. (2022), "Exhaust emissions reduction and fuel consumption from the L.N.G. energy system depending on the ship operating modes", *Pomorstvo*, Vol. 36 No. 2, pp. 338-346, doi: 10.31217/p.36.2.17.

Maurer, R., Kossioris, T., Hausberger, S., Toenges-Schuller, N., Sterlepper, S., Günther, M. and Pischinger, S. (2023), "How to define and achieve Zero-Impact emissions in road transport?", *Transportation Research Part D: Transport and Environment*, Vol. 116, 103619, doi: 10.1016/j.trd.2023.103619.

Maydanova, S., Ilin, I. and Jahn, C. (2019), "Balanced scorecard for the digital transformation of global container shipping lines", *International Conference on Digital Transformation in Logistics and Infrastructure (ICDTLI 2019)*, Atlantis Press.

Meca, V.L., Villalba-Herreros, A., d'Amore-Domenech, R. and Leo, T.J. (2022), "Zero emissions wellboat powered by hydrogen fuel cells hybridised with batteries", *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 236 No. 2, pp. 525-536, doi: 10.1177/14750902211046165.

Mir, M.A., Ghazvinei, P.T., Sulaiman, N.M., Basri, N.E., Saheri, S., Mahmood, N.Z., Jahan, A., Begum, R.A. and Aghamohammadi, N.J.J.O.E.M. (2016), "Application of T.O.P.S.I.S. and V.I.K.O.R. improved versions in a multi criteria decision analysis to develop an optimised municipal solid waste management model", *Journal of Environmental Management*, Vol. 166, pp. 109-115.

Mollaoglu, M., Demirel, H. and Balin, A. (2022), "Evaluation of the effects of industry 4.0 on the maritime sector with fuzzy ahp–vikor hybrid method", *International Journal of Maritime Engineering*, Vol. 164 No. A2, pp. 135-146, doi: 10.5750/ijme.v164ia2.778.

Mondejar, M.E., Andreasen, J.G., Pierobon, L., Larsen, U., Thern, M. and Haglind, F. (2018), "A review of the use of organic Rankine cycle power systems for maritime applications", *Renewable and Sustainable Energy Reviews*, Vol. 91, pp. 126-151, doi: 10.1016/j.rser.2018.03.074.

Moreno-Gutiérrez, J., Pájaro-Velázquez, E., Amado-Sánchez, Y., Rodríguez-Moreno, R., Calderay-Cayetano, F. and Durán-Grados, V. (2019), "Comparative analysis between different methods for calculating on-board ship's emissions and energy consumption based on operational data", *Science of the Total Environment*, Vol. 650, pp. 575-584, doi: 10.1016/j.scitotenv.2018.09.045.

Muda, I., Erlina, I.Y. and A, A.N. (2018), "Performance audit and balanced scorecard perspective", *International Journal of Civil Engineering and Technology*, Vol. 9 No. 5, pp. 1321-1333.

Nazim, M., Mohammad, C.W. and Sadiq, M. (2022), "A comparison between fuzzy AHP and fuzzy TOPSIS methods to software requirements selection", *Alexandria Engineering Journal*, Vol. 61 No. 12, pp. 10851-10870.

Nishio, S., Fukuda, T., Fathallah, A.Z.M.S. and Setiapraja, H. (2018), "Influence of palm biofuel for marine diesel engine on combustion and exhaust emission characteristics", *Marine Engines*, Vol. 53 No. 3, pp. 441-446, doi: 10.5988/jime.53.441.

Park, K.S., Seo, Y.J., Kim, A. and Ha, M.H. (2018), "Ship acquisition of shipping companies by sale & purchase activities for sustainable Growth: exploratory fuzzy-AHP application", *Sustainability*, Vol. 10 No. 6, p. 1763, doi: 10.3390/su10061763.

Peña, L.E., Zapata, M.A. and Barrios, M. (2019), "Analytic hierarchy process approach for the selection of stream-gauging sites", *Hydrological Sciences Journal*, Vol. 64 No. 14, pp. 1783-1792, doi: 10.1080/02626667.2019.1672874.

Qu, J., Feng, Y., Xu, G., Zhang, M., Zhu, Y. and Zhou, S. (2022), "Design and thermodynamics analysis of marine dual fuel low speed engine with methane reforming integrated high pressure exhaust gas recirculation system", *Fuel*, Vol. 319, 123747, doi: 10.1016/j.fuel.2022.123747.

Qu, Z., Wan, C., Yang, Z. and Lee, P.T.W. (2018), "A discourse of multicriteria decision making (M.C.D.M.) approaches", edited by Mak, M.-C.D.

Rojas, N.Y., Mangones, S.C., Osses, M., Granier, C., Laengle, I., Alfonso, A.J.V. and Mendez, J.A. (2023), "Road transport exhaust emissions in Colombia. 1990-2020 trends and spatial disaggregation", *Transportation Research Part D: Transport and Environment*, Vol. 121, 103780, doi: 10.1016/j.trd.2023.103780.

Roy, W., Scheldeman, K., Roozendael, B., Nieuwenhove, A., Schallier, R., Vigin, L. and Maes, F. (2022), "Airborne monitoring of compliance to NOx emission regulations from ocean-going vessels in the Belgian North Sea", *Atmospheric Pollution Research*, Vol. 13 No. 9, 101518, doi: 10.1016/j.apr.2022.101518.

Sakhardande, M.J. and Gaonkar, R.S.P. (2022), "On solving large data matrix problems in Fuzzy AHP", *Expert Systems with Applications*, Vol. 194, 116488, doi: 10.1016/j.eswa.2021.116488.

Šaković Jovanović, J., Fragassa, C., Krivokapić, Z. and Vujović, A. (2019), "Enviromental management systems and balanced scorecard: an integrated analysis of the marine transport", *Journal of Marine Science and Engineering*, Vol. 7 No. 4, p. 119, doi: 10.3390/jmse7040119.

Samasm, K.M.H.R., Ragab, M.H., Adam Hebatallah and Gamil, A.F.M. (2018), "A proposed model for activating safety and occupational health programs using the balanced scorecard (B.S.C.) case study on ain shams specialized hospital", *Journal of Environmental Science*, Vol. 42 No. 2, pp. 401-426, doi: 10.21608/jes.2018.22105.

Sanchez-Gonzalez, P.L., Díaz-Gutiérrez, D. and Núñez-Rivas, L.R. (2022), "Digitalising maritime containers shipping companies: impacts on their processes", *Applied Sciences*, Vol. 12 No. 5, p. 2532, doi: 10.3390/app12052532.

Schröder, J., Hartmann, F., Eschrich, R., Worch, D., Böhm, J., Gläser, R. and Müller-Langer, F. (2017), "Accelerated performance and durability test of the exhaust aftertreatment system by contaminated biodiesel", *International Journal of Engineering Research*, Vol. 18 No. 10, pp. 1067-1076, doi: 10.1177/1468087417700762.

Sirviö, K. (2018), "Issues of various alternative fuel blends for off-road, marine and power plant diesel engines", Doctoral thesis by Publication University of Vassa.

Skolarikos Maritime Bureau (2022), "Skolarikos communication catalogue".

Sofiev, M., Winebrake, J.J., Johansson, L., Carr, E.W., Prank, M., Soares, J., Corbett, J.J., Kouznetsov, R. and Jalkanen, J.P. (2018), "Cleaner fuels for ships provide public health benefits with climate tradeoffs", *Nature Communications*, Vol. 9 No. 1, p. 406, doi: 10.1038/s41467-017-02774-9.

Stathatou, P.M., Bergeron, S., Fee, C., Jeffrey, P., Triantafyllou, M. and Gershenfeld, N. (2022), "Towards decarbonisation of shipping: direct emissions & life cycle impacts from a biofuel trial aboard an ocean-going dry bulk vessel", *Sustainable Energy and Fuels*, Vol. 6 No. 7, pp. 1687-1697, doi: 10.1039/d1se01495a.

Sun, Y., Hu, Y., Zhang, H., Chen, H. and Wang, F.-Y. (2023), "A parallel emission regulatory framework for intelligent transportation systems and smart cities", *IEEE Transactions on Intelligent Vehicles*, Vol. 8 No. 2, pp. 1017-1020, doi: 10.1109/TIV.2023.3246045.

Szczepański, K., Bebkiewicz, K., Chłopek, Z., Sar, H. and Zakrzewska, D. (2023), "Analysis of the national annual emission of pollutants from road transport in Poland in the years 1990-2020", *Energies*, Vol. 16 No. 10, p. 4083, doi: 10.3390/en16104083.

Thalis, Z. and Psaraftis, H.N. (2018), "Key performance indicators to assess and reverse the negative impacts of S.E.C.A.s policies for Ro-Ro shipping", *FME Transactions*, Vol. 46 No. 3, pp. 347-354, doi: 10.5937/fmet1803347z.

Thengane, S. K., Hoadley, A., Bhattacharya, S., Mitra, S. and Bandyopadhyay, S. (2014), "Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP", *International journal of hydrogen energy*, Vol. 39 No. 28, pp. 15293-15306.

Tran, T.A. (2017), "Research of the scrubber systems to clean marine diesel engine exhaust gases on ships", *Journal of Marine Science: Research and Development*, Vol. 7 No. 6, p. 243, doi: 10.4172/2155-9910.1000243.

Tsitsilonis, K.M. and Theotokatos, G. (2018), "A novel systematic methodology for ship propulsion engines energy management", *Journal of Cleaner Production*, Vol. 204, pp. 212-236, doi: 10.1016/j.jclepro.2018.08.154.

Tyrovola, T., Dodos, G., Kalligeros, S. and Zannikos, F. (2017), "The introduction of biofuels in marine sector", *Journal of Environmental Science and Engineering A*, Vol. 6 No. 8, pp. 415-421, doi: 10.17265/2162-5298/2017.08.006.

Vallapudi, D.R., Makineni, H.K., Pisipaty, S.K. and Venu, H. (2018), "Combined impact of EGR and injection pressure in performance improvement and NOx control of a DI diesel engine powered with tamarind seed biodiesel blend", *Environmental Science and Pollution Research*, Vol. 25 No. 36, pp. 36381-36393, doi: 10.1007/s11356-018-3540-7.

Venkatesh, V.G., Zhang, A., Deakins, E., Luthra, S. and Mangla, S. (2019), "A fuzzy AHP-TOPSIS approach to supply partner selection in continuous aid humanitarian supply chains", *Annals of Operations Research*, Vol. 283 No. 1, pp. 1517-1550, doi: 10.1007/s10479-018-2981-1.

Wang, H., Oguz, E., Jeong, B. and Zhou, P. (2018), "Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry", *Ocean Engineering*, Vol. 161, pp. 20-28, doi: 10.1016/j.oceaneng.2018.04.084.

Watanabe, M.D., Cherubini, F., Tisserant, A. and Cavalett, O. (2022), "Drop-in and hydrogen-based biofuels for maritime transport: country-based assessment of climate change impacts in Europe up to 2050", *Energy Conversion and Management*, Vol. 273, 116403, doi: 10.1016/j.enconman.2022.116403.

Wei, L., Cheng, R., Mao, H., Geng, P., Zhang, Y.Y. and K. (2018), "Combustion process and NOx emissions of a marine auxiliary diesel engine fuelled with waste cooking oil biodiesel blends", *Energy*, Vol. 144, pp. 73-80, doi: 10.1016/j.energy.2017.12.012.

Yasin, M.H.M., Mamat, R., Yusop, A.F., Idris, D.M.N.D., Yusaf, T., Rasul, M. and Najafi, G. (2017), "Study of a diesel engine performance with exhaust gas recirculation (EGR) system fuelled with palm biodiesel", *Energy Procedia*, Vol. 110, pp. 26-31, doi: 10.1016/j.egypro.2017.03.100.

Zannis, T.C., Katsanis, J.S., Christopoulos, G.P., Yfantis, E.A., Papagiannakis, R.G., Pariotis, E.G. Vallis, A.G. and Rakopoulos, C.D. (2022), "Marine exhaust gas treatment systems for compliance with the I.M.O. 2020 global sulfur cap and Tier III NOx limits: a review", *Energies*, Vol. 15 No. 10, p. 3638, doi: 10.3390/en15103638.

Zhang, X. and Lam, J.S.L. (2019), "A fuzzy Delphi-AHP-TOPSIS framework to identify barriers in big data analytics adoption: case of maritime organisations", *Maritime Policy and Management*, Vol. 46 No. 7, pp. 781-801, doi: 10.1080/03088839.2019.1628318.

Zhang, Y., Xia, C., Liu, D., Zhu, Y. and Feng, Y. (2023), "Experimental investigation of the high-pressure S.C.R. reactor impact on a marine two-stroke diesel engine", *Fuel*, Vol. 335, 127064, doi: 10.1016/j.fuel.2022.127064.

Corresponding author
Hristos Karahalios can be contacted at: hristos.karahalios@solent.ac.uk