

Evaluation of Constraints for Investment in NOx Emission Technologies: Case Study on Greek Bulk Carrier Owners

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 had to adopt strategies and new technologies to eliminate air pollution. However, ship compliance with Nitrate Oxide (NOx) emissions restrictions is more challenging. This paper aims to identify ship owners' challenges in investing in new technologies.

Design/methodology/approach

This paper applied a hybrid methodology combining a survey, Balanced Scorecard and Fuzzy Analytic Hierarchy Process (F-AHP) to identify and evaluate constraints and weight 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 weighting list of seven crucial technical and economic constraints 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 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 ship owners. 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

1. Introduction

NOx emission reduction is an essential challenge in all transport sectors (Hwang *et al.*, 2023). The maritime transport sector is argued to contribute most of NOx emissions. The air pollution caused by ships to 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 the engine type and the 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 SO_x 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).

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 of sulphur content in fuels to 0.5% after 1 January 2020, and additional restrictions in some geographical regions named Emission Control Areas for Sulphur (SECA) and NO_x (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 Required Energy Efficiency Design Index (REEDI) (Kostova *et al.*, 2023).

The focus on NO_x emissions specifically is a key contributor to air pollution, including smog formation and acid rain, making it a priority for regulatory intervention. Additionally, reducing NO_x emissions aligns with broader environmental goals and commitments from ship operators to combat climate change. Ship operators are required to comply with NO_x 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 ship's 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 ship owners hesitate to invest in some NO_x reduction technologies. The

research focuses on the maritime sector because it contributes the largest NO_x 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 are presented in Section 5.

2. Literature Review on NO_x Emission Technologies

Concerning NO_x 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 NO_x emissions (Sun *et al.*, 2023). Studies investigating alternatives for NO_x 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 NO_x (Chorowski *et al.*, 2023). However, the majority of these research studies focus on the technical feasibility of various NO_x 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 retarded injection timing to minimise NO_x. However, it is complicated to meet TIER III requirements (Czmyr and Kaminski, 2019). More precisely, ship operators must select their strategy to comply with NO_x emission regulations until the world fleet complies with IMO Tier III requirements. From the ship operator's viewpoint, compliance with NO_x emission 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 are presented available technologies.

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 NO_x, as per TIER II. Installing an Exhaust Gas Recirculation (EGR) system is a solution to meet this goal. Eriksson and Llamas (2020) described this method that recirculates exhaust gases into the engine. This technology mitigates ship NO_x emissions by recirculating a portion of exhaust gases into the engine's combustion chamber. EGR could effectively meet the IMO Tier III by reducing NO_x 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 is approaching port or manoeuvring during berthing (Llamas and Eriksson, 2019).

2.2 Selective Catalytic Reduction (SCR) system

Another option for ship operators to achieve a reduction of NO_x 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 NO_x reduction. More advanced solutions are high-pressure-SCR system 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 NO_x 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 using other types of fuels. Recent studies favour alternative maritime fuels, such as LNG, drastically reducing NO_x emissions (Livaniou *et al.*, 2022). Designing ship fuel powered with 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 NO_x 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 NO_x goals by 2050 as it causes methane slip (Agarwala, 2022). Also, the LNG vessels and their equipment have different power consumption requirements at sea on 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 of biofuels have been tested in a large Kamsarmax dry bulk carrier, showing NO_x emissions 3% lower than LSMGO (Stathatou *et al.*, 2022). Hydrogen-based biofuels' produce slightly lower climate impacts concerning NO_x (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 NO_x emissions, biofuels have negative results (Nishio *et al.*, 2018). The better NO_x reduction depends on blended biodiesel ratios (Wei *et al.*, 2018). Nevertheless, Biofuels are insufficient for NO_x 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 (Güven and Kayalica, 2023a).

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 ships. Recent research has revealed that differentiation in the awareness and views among shipowners is a significant obstacle to adapting this technology at ports (Kim *et al.*, 2023). When examining a 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 NO_x emissions (Güven and Kayalica, 2023b). An alternative to SCR or EGR for ocean voyage ships is using LNG and batteries to reduce the NO_x of ship exhausts (Laribi and Guy, 2023; Mondejar *et al.*, 2018). Another option is Hydrogen fuel cells hybridised installed on an exposed deck with batteries that can provide ship power from 1266 kW to 2624 kW without emission of NO_x (Meca *et al.*, 2022).

3. Research Methodology

The proposed methodology aims to evaluate which of the NO_x reduction technologies causes fewer constraints and which a ship operator would prefer to invest. The input of this research is to utilise a hybrid model of F-AHP investigating investment constraints with these technologies. It also provided the mechanism to analyse ship owners' most preferred technologies in 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:

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

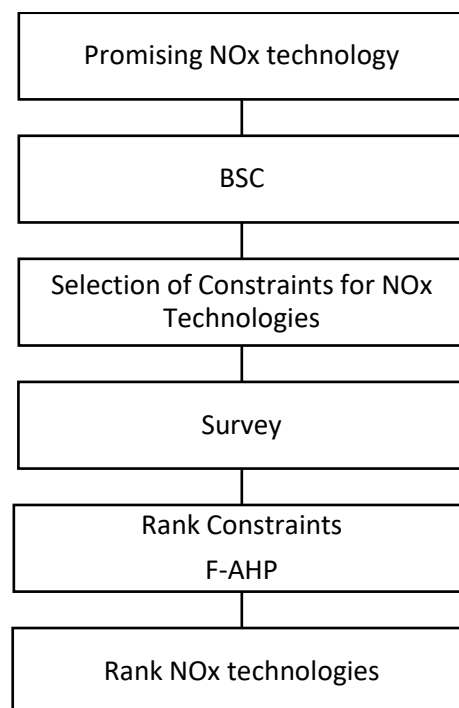


Figure 1. Research Methodology

3.1 Selected Constraints for NOx Technologies

After identifying the available NOx technologies, the next step is identifying each 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 NO_x 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 Balanced Scorecard (BSC) is the most appropriate since it includes non-economic 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 & Growth perspectives (Samasm *et al.*, 2018). The generated scorecard, with fewer than twenty 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, 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 NO_x emissions from marine engines. Including studies showing techno-economical and operation challenges with equipment used to eliminate SO_x emissions from ships is also crucial. By applying BSC, selected studies can be used to identify constraints 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 NO_x technologies suitable for TIER III. Following the BSC approach, Financial perspective measures are needed to determine if the adoption of NO_x Technology could be proven cost-effective. Ship operators are hesitant to invest in new technologies due to knowledge limitations of their economic efficiency (Livaniou *et al.*, 2022; Thalís 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 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 a 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, 2018; Mir *et al.*, 2016).

Concerning Learn & Growth perspective, any ship modifications require seafarers to be trained for ship-specific actions, including fuel switchover, bunker scenarios and 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.

Table 1. Proposed Technical Constraints

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, 2018 Mir et al., 2016 Başhan et al., 2022
Learn & Growth	Crew Training	Wang et al., 2018 Laribi and Guy, 2023

3.3 Prioritisation of Constraints with F-AHP

Some research suggests that a BSC scorecard could be used to shape a hierarchal 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 Fuzzy Analytic Hierarchy Process (F-AHP) is employed to determine their significance. Employing F-AHP is a structured approach that enhances the robustness of analysing ship owners' 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.

sation of constraints, aiding ship owners 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).

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 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).

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)

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} ($i, j = 1, 2, 3, \dots, n$) is evaluated by multiple pairwise comparisons. The linguistic scale for each a_{ij} shows the importance of a_i over a_j where $a_{ji} = 1/a_{ij}$ adopts the principal eigenvalue (Park *et al.*, 2018; Peña *et al.*, 2019). Then, an estimation of the eigenvector is calculated as with Eq. (1). F-AHP calculations can be used for further analysis of each responder or Group (Sakhardande and Gaonkar, 2022). It is, therefore, 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 (Li *et al.*, 2019). 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).

$$w_i = \frac{1}{n} \frac{\sum_{j=1}^n a_{ij}}{\sum_{k=1}^n a_{kj}} \quad \text{Equation (1)}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{Equation (2)}$$

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

3.4 Survey design

3.1. 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 availability of NOx minimisation technologies should meet ship managers' demand for these technologies in the maritime industry. To fulfil the research aims, a survey is required in this study. The survey's main point is to identify the Most Promising Technology for NOx Reduction they would invest in. The sampling plan is for companies managing ships located in Greece. A review of the Shipping Intelligence database (Network, 2022) reveals that Greek ship owners invested in technologies such as LNG, SOx Scrubber, Eco-Electronic Engine, and Biofuel. Table 3 shows technologies until July 2022 4,615 with a 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.

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

NOx technologies	Ships
Eco – Electronic Engine Modern	1099
LNG Capable	129
SOx Scrubber Status	817
LNG Ready	18
Biofuel	3
Eco - Electronic Engine	0
Alternative Fuel Types	0

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 responders 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 with 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 3 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 on new NO_x technologies. The second section includes questions regarding the demographics of respondents and their companies. The third section was for responders 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 NO_x Reduction. This second question is about a strategy to comply with existing SO_x requirements that have already been enforced. With this approach, a more holistic idea of investing approach 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 million DWT. In this survey, 14,562,000 DWT represents 4 % of that fleet or 5.1 % of Greek-owned ships. As shown in Table 4, the responders 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.

Table 4. Responders' Qualifications

Academic Qualification	Position	Years of Managerial Experience
PhD	Safety Management	More than 10
MSc	Technical Management	More than 10
MSc	Technical Management	Between 6 and 10
MSc	Safety Inspection/Audit/Accident Investigation	Less than 5
MSc	Technical Management	More than 10
BSc	Technical Management	More than 10
MSc	Technical Management	More than 10

Each expert had to make a pairwise comparison for each constraint using the linguistic terms of 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 linguistic terms for this pairwise comparison is found to be (0.77, 0.90, 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 in the matrix shown in Table 6. With this approach, it was possible to have a pairwise comparison matrix with crisp numbers. The matrix in Table 6 represents the average crisp values of all expert's judgments. 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' judgments.

Table 5. Example of Experts' Judgments 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

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

The constraints were weighed with operations, as shown in Section 3.1 and presented in Table 7. Based on the findings, it appears that the most critical constraints in investing are Installation Cost and the Price of Fuel. Crew Training and Higher Fuel Consumption ranked third and fourth, respectively, followed by Fuel Tanks 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 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 in Group 3 ships larger than 80.000 DWT. Interestingly, when examining replies with SOx, most ships did not invest in technology.

Table 7. Ranking of Constraints

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

Table 8. Comparison of Groups with SOx Strategy

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

Therefore, it was necessary to examine how each Group prioritised constraints and how they would prefer to vest for 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 Tanks Capacity. 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.

Table 9. Ranking of Constraints of Each Group

	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
Owerconsumption	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

As there are different priorities, the survey outcome was that there are differences between Groups in the ranking of NOx technologies. Table 10 shows the result 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.

Table 19. Ranking of NOx technologies

	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

5. Discussion & 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 from the literature were seven. Those can be adopted in similar studies and used by any ship operator. The benefit of 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 on those technologies that use less costly fuels, which could determine future ship design. 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, particularly shipowners. The contribution of this study is that it reveals the cost and non-economic constraints that ship operators will face with compliance with NOx emission TIER III requirements. The data show that Bunker Price of Fuels, Higher Fuel Consumption, Installation Cost, and Fuel Tanks Capacity are essential constraints for decision-makers investing in new technologies. Experts concluded that the highest factors ranked include 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 in 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 beneficial when validating the model and expertise of participants. A robust model is presented, which could easily apply 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 similar survey to other parts of transport modes

and other types of ships is recommended. This paper contributed 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. 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.

6. References

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