Doctoral Programme in Interdisciplinary Environmental Sciences
Faculty of Biological and Environmental Sciences
University of Helsinki

Dissertationes Universitatis Helsingiensis
259/2025

Multi-criteria decision analysis in the search of sustainable maritime emission management

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DOCTORAL DISSERTATION

To be presented for public discussion, with the permission of the Faculty of
Biological and Environmental Sciences of the University of Helsinki,
in lecture room 1041, Biocentre 2,
on 5 September 2025, at 13 o’clock.

Helsinki 2025

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Publisher: University of Helsinki
Series: Dissertationes Universitatis Helsingiensis 259/2025

ISBN 978-952-84-1117-8 (print)
ISBN 978-952-84-1116-1 (online)
ISSN 2954-2898 (print)
ISSN 2954-2952 (online)

Unigrafia / PunaMusta
Joensuu 2025

Abstract

A significant transformation is occurring within the domain of maritime transportation, with the objective of reducing the sector's detrimental environmental impact. This encompasses both direct and indirect emissions generated by the propulsion systems of ships, as well as numerous other practices employed in maritime operations. The implementation of new regulations, such as the FuelEU Maritime and the EU Emission Trading System, has compelled a transition away from fossil-based fuels as the primary source of power in maritime transport. The expansion of the emission trading system to maritime transport increases fossil fuel costs for shipowners. In addition to the source of propulsion power, energy efficiency must also be improved, which is regulated, for example, by the energy efficiency design index (EEDI), the energy efficiency existing ship index (EEXI), and the carbon intensity indicator (CII), launched by the International Maritime Organization (IMO). A biofouling management plan is a key component of a comprehensive energy efficiency strategy aimed at minimizing fuel and energy consumption in maritime transport. It is an element of the ship energy efficiency management plan (SEEMP).

While global warming is a serious issue that demands immediate attention, a holistic approach to planning is crucial to prevent the adoption of solutions that might create new problems in different contexts. For example, decisions regarding emission reductions must consider not only greenhouse gases but also other types of environmental pollution and their human health impacts. Correspondingly, air emissions should be considered when aiming to manage other types of pollution and risks. Achieving sustainable development objectives requires the consideration and balancing of often conflicting requirements, thus creating multi-criteria decision-making problems. Defining the optimal or "most sustainable" solution is often ambiguous and strongly depends on the chosen approach to sustainability.

Consisting of four Articles (I-IV) and the summary section, this thesis presents two multi-criteria decision analysis applications for considering the impacts of decisions aimed at advancing the sustainable development of maritime transport sector. The focus of the contribution is specifically on the air emissions as part of the multi-criteria management choices. Articles I - II present the model that enables life cycle emission-based comparison of three fossil fuels (heavy fuel oil, marine gas oil, liquefied natural gas) and selected air emission abatement systems (selective catalytic reduction, water-in-fuel, exhaust gas recirculation, open and closed loop scrubbers) from both environmental and economic standpoints. Articles III and IV

present a complex decision problem and a computational model for biofouling management in shipping in the Baltic Sea region, considering carbon dioxide emissions, fuel costs, and ecotoxicological and ecological risks.

In this thesis summary, I discuss the properties, advantages and disadvantages, critical issues, and future development needs of the two modeling applications. The models have key fundamental differences in how they address and represent sustainability, which affects their potential use as decision support tools. The Excel-based decision model presented in Articles I-II uses measurable input values and user selected weights to generate integrated index-based results for the concept. This approach facilitates the comparative analysis of otherwise challenging-to-compare elements, and also allows for computational optimization. However, a challenge with such integrated, index-based approaches is the potential loss of information that may be necessary or useful for the decision-making process. In addition, the selection of mutual weights for sustainability dimensions and their implications for outcomes are crucial from a user perspective. The Bayesian Network-based model outlined in Article III employs a parallel presentation of its multiple assessment endpoints, enabling the consideration of incommensurable outcomes transparently, without the need for artificial summaries. The model also provides the outcomes of different decision options as probability distributions, enabling the analyst to better assess the sensitivity of the results. However, a comparison of this model with the qualitative conceptual representation of the decision problem in its full complexity, presented in Article IV, reveals numerous simplifications arising from limitations in data and the computational approach. Finally, it is imperative to acknowledge that the successful implementation of any model is contingent upon the user's understanding of its application within the relevant context. The optimal model is one that is suitable for its intended use, considering the expertise of the users, the availability of data and software, and other resources as well. This also determines what kind of end user can ultimately benefit from using the model.

Acknowledgements

Writing a dissertation is a long process that requires engagement with many different parties. Time often passes more quickly than one realizes. Fortunately, even lengthy projects can be brought to a successful conclusion.

I would like to express my sincere gratitude to Associate Professor (Docent) Annukka Lehikoinen (University of Helsinki and Kotka Maritime Research Centre, Finland), who has served as my supervisor and, prior to that, as a research colleague during the implementation of the two "COMPLETE" projects. I would also like to thank the members of the thesis committee, Professor Sirkku Juhola and Assistant Professor Sanna Ala-Mantila (both from University of Helsinki), for their valuable feedback and support.

I am grateful to Professor Risto Soukka from Lappeenranta-Lahti University of Technology LUT for serving as my opponent, and to Professor Sakari Kuikka from University of Helsinki for acting as my Custos and Coordinating Academic. I also wish to thank the preliminary examiners, Reader Dr. Christos Kontovas from Liverpool John Moores University (United Kingdom) and Research Fellow Dr. Joseph Guillaume from Australian National University (Australia), for their constructive and valuable feedback.

I would like to thank all my co-authors, Taru Tanhuanpää, Dr. Sirpa Rahiala, Marko Piispa, Dr. Emilia Luoma, Lauri Nevalainen, Dr. Inari Helle, Dr. Mirka Laurila-Pant, Associate Professor Lena Granhag, Professor Maiju Lehtiniemi, Dr. Greta Srėbalienė and Professor Sergej Olenin. In addition, I extend my special thanks to South-Eastern Finland University of Applied Sciences (XAMK) for its excellent and strong support throughout the dissertation process. I would also like to express my gratitude to the companies, authorities, and associations who participated or otherwise provided practical support in this research process (in alphabetical order: AS Tallink Grupp, DG Diving Group, Finnish Environment Institute, Finnish Meteorological Institute, Finnish Transport and Communications Agency, Finnish Transport Infrastructure Agency, Finnish Shipowners' Association, Finnlines, Gasum, Kotka Maritime Research Centre, Neste, Port of HaminaKotka, MeriAura, Silja Line, Viking Line, Wärtsilä).

This work was carried out as part of the following research projects: "COMPLETE" (Completing Management Options in the Baltic Sea Region to Reduce Risk of Invasive Species Introduction by Shipping, project #R069, Interreg

Baltic Sea Region), “COMPLETE PLUS” (Practical Implementation of the “COMPLETE” Project Outputs and Tools, project #023, Interreg Baltic Sea Region), “MEPTEK” (Benchmarking Study of Marine Emission Reduction Technologies, A75791, European Regional Development Fund) and “MERPOL” (Renewable Fuels – Support for the Sustainable and Carbon-Neutral Growth of Maritime Transport, A80430, European Regional Development Fund). I would like to express my sincere gratitude to our funders, namely the Interreg Baltic Sea Region Programme, the Kymenlaakso Regional Council and the Uusimaa Regional Council, whose financial support made this research possible.

I would like to express my gratitude to my family; including my wife Anne-Mari and our children Antoni, Ada, Emilia, and Annabel; my parents Antonio and Arja; my sister Laura and her family; my wife’s sister Satu and her family; other relatives such as Sari, Susanna, and Inka; and all friends, especially Tero and his family, as well as crew members from the Finnish Lifeboat Institution, for their continued support.

List of abbreviations

AP	Acidification potential
BN	Bayesian network
CID	Conceptual influence diagram
CII	Carbon Intensity Indicator
CLS	Closed-loop scrubber
EcI	Economical index
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGR	Exhaust gas recirculation
EnvI	Environmental index
EP	Eutrophication potential
ETS	Emission Trading System
GWP100	Global warming potential (100 years)
HFO	Heavy fuel oil
HHPA	Human health particulate air potential
ID	Influence diagram
IMO	International Maritime Organization
IWC	In-water cleaning
LNG	Liquefied natural gas
MARPOL	Marine Pollution (IMO MARPOL Convention, 1973/78)
MCDA	Multi-criteria decision analysis
MCDAM	Multi-criteria decision analysis model
MCSIM	Multi-criteria sustainable index model
MGO	Marine gas oil
MRV	Monitoring, Reporting and Verification (EU regulation)
NIS	Non-indigenous species
OLS	Open-loop scrubber
RFNBO	Renewable fuels of non-biological origin
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SusI	Sustainability index
WIF	Water-in-fuel system

Index

List of original publications and author's contribution

This thesis is based on the following Articles:

I Altarriba, E., Rahiala, S., Tanhuanpää, T., Lehikoinen, A., (2025). Comparing fuels and emission reduction techniques for sustainable shipping: a sustainability index weighting life cycle emissions and costs. *Journal of Cleaner Production*, 495, 145037. https://doi.org/10.1016/j.jclepro.2025.145037

II Altarriba, E., Rahiala, S., Tanhuanpää, T., Piispa, M., (2024). Developing sustainable shipping and maritime transport: multi-criteria analysis between emission abatement methods. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 238(2), 364-374. https://doi.org/10.1177/14750902231199132

III Luoma, E., Laurila-Pant, M., Altarriba, E., Nevalainen, L., Helle, I., Granhag, L., Lehtiniemi, M., Srėbalienė, G., Olenin, S., Lehikoinen, A. (2022). A multi-criteria decision analysis model for ship biofouling management in the Baltic Sea. *Science of the Total Environment*, 852, 158316. https://doi.org/10.1016/j.scitotenv.2022.158316

IV Luoma, E., Nevalainen, L., Altarriba, E., Helle, I., Lehikoinen, A. (2021). Developing a conceptual influence diagram for socio-eco-technical systems analysis of biofouling management in shipping – A Baltic Sea case study. *Marine Pollution Bulletin*, 170, 112614. https://doi.org/10.1016/j.marpolbul.2021.112614

In the text, the Articles are referred to using Roman numerals.

Author’s contribution to the articles:

I In the context of the MCSIM development research project, Altarriba assumed the role of project manager and was responsible for supervising the research team. The analysis and data collection were conducted by Altarriba, Rahiala, and Tanhuanpää. Rahiala was the primary developer of the MCSIM analysis tool, with input from Altarriba and Tanhuanpää. The responsibility for the writing process was shared by Altarriba, Rahiala, Tanhuanpää, and Lehikoinen.

II This publication presents the first version of MCSIM presented in Article 1. Altarriba served as the project manager, and all authors were responsible for data collection. However, Altarriba, Rahiala, and Tanhuanpää were primarily responsible for analysis. Rahiala was the primary developer of the MCSIM analysis tool, receiving input from all other authors. Altarriba, Rahiala, and Tanhuanpää were responsible for the writing process, while Piispa served as a commentator.

III In the complex integrated model entity presented, Altarriba played an independent role in developing elements related to the link between biofouling and ship energy consumption, as evidenced by two peer-reviewed publications provided below. He also actively contributed to the planning, writing, and revision processes of the article. Altarriba was the principal investigator for the related project work package at South-Eastern Finland University of Applied Sciences.

IV Altarriba was responsible for the collection and analysis of data regarding the link between biofouling, ships’ fuel consumption, and emissions. He also contributed actively to the planning, writing, and revision of the article. Altarriba was the principal investigator for the related project work package at South-Eastern Finland University of Applied Sciences. He made a notable independent contribution to this article related to ship emissions.

1 Introduction

1.1 Background

The impact of maritime transport on societies is considerable: maritime transport virtually enables the existence of international and global economic system, with significant multiplier effects on societies worldwide (Ferrari et al., 2023). In addition to providing free access to international waters, the cost structure of the maritime logistics sector is effective. When evaluated in terms of ton-miles of cargo transported, maritime transport has been shown to be both cost effective and energy efficient compared to other modes of transport. Furthermore, maritime transport is characterized by high cargo volumes (Lindstad & Eskeland, 2015). However, such volumes have also been associated with significant environmental impacts (Tatar & Özer, 2018; Trosvik & Brynolf, 2024). A multitude of regulations have been introduced with the objective of reducing air emissions from ships. These include regulations introduced by the International Maritime Organization (IMO) and the European Union (EU). Furthermore, the spread of invasive species, marine litter, wastewater treatment, and accidental marine pollution have been identified as areas of focus for mitigation (IMO, 1973, updated Annexes I-VI). Achieving these objectives in practice is not straightforward. In many cases, no optimal solution can be identified, and decision-making must involve a trade-off between adverse impacts and the benefits gained. Investments in maritime logistics are frequently considerable and long-term. Consequently, investment decisions and other strategic choices made will have long-term consequences for stakeholders (Aakko-Saksa et al., 2023). The facilitation of the decision-making process necessitates the development of tools and methodologies, which can be crucial for elucidating the underlying choices, discerning the nuances between competing alternatives, and quantifying associated risks (Uusitalo et al., 2015). The objective is to prevent the selection of an initially favorable option that may prove unsustainable soon.

A significant number of resources is currently being allocated to advancing sustainable development and the green transition globally (Elliot et al., 2017; Barrow et al., 2005; Jager & Mosler, 2007; Reum et al., 2021). As part of this process, legislation is being reformed at national, regional (e.g., the EU), and global levels (e.g., the IMO) to eliminate the most harmful practices and replace them with more sustainable alternatives (EU 2023/1805; EU 2023/959). However, sustainability is inherently multifaceted and can be approached from environmental, economic and social perspectives. Together, these perspectives form a holistic understanding of sustainability (Brundtland, 1987; Giddings et al., 2002). Environmental sustainability refers to minimizing activities that are known to cause environmental harm. The economy can be understood as a system of interactions between people. Economic sustainability, therefore, concerns the system's ability to remain viable under varying conditions. Social sustainability offers a human-centered perspective, with a particular focus on the complex societal impacts of economic activity. Nonetheless, environmental sustainability also plays a significant role in this context.

The perception of sustainability is subject to change over time. Many technologies or practices that were once widely regarded as sustainable have later proven to be problematic (Kuhlman & Farrington, 2010; Shrivastava & Berger, 2010). These concerns span a broad range of sectors, including, but not limited to, energy and fuel production, transportation infrastructure, and power systems. A similar set of megatrend developments has been observed in the domain of maritime transport. The transition from wooden ships to steel hulls necessitated a reduction in the quantity of lumber required. However, at the same time, the mining and steel industries were compelled to increase production volumes to unprecedented levels (Coates & Coates, 1999). The coal-powered steam engine rooms were particularly harsh and unhealthy working environments for the engine room staff. Moreover, the steam engines and boilers required long heating periods and were large and heavy machines. Consequently, the transition to diesel internal combustion engines powered by fuel oils appeared to be a promising solution (Corbett, 2004). The use of heavy fuel oils as a fuel enabled the effective utilization of residual oils, especially in merchant ships (Harrold, 1988). The dispersion of flue gases into the marine environment was rapid, and ports were frequently contaminated by the industrial sector, so the impact of ships on port air quality was not considered a concern (Becker & Henderson, 2000).

Subsequent to that time, the circumstances have changed significantly. Global warming has caused a global climate crisis (IPCC, 2022). Acidification and eutrophication, particularly in shallow or isolated sea areas, have been identified as a substantial environmental problem (Jutterström et al., 2021). The associated human health implications have become a pivotal issue, especially concerning operations in ports or fairways located near settlements (Barregard et al., 2019; Viana et al., 2014; Viana et al., 2020). In addition, environmental concerns have expanded beyond air emissions. A significant issue is the introduction of invasive alien species (Ojaveer et al., 2017), which have been shown to negatively impact on native species. Globally, the introduction of alien species ranks as the second leading cause of extinction, following habitat destruction (Molnar et al. 2008). Ships' ballast water is a well-documented vector for the dispersal of marine alien species (Olenin et al., 2016). Consequently, an international ballast water management agreement has been established to regulate this phenomenon (IMO, 2004). Biofouling on immersed hull structures has received comparatively less attention than other vectors. However, in recent years, there has been an increase in research focusing on this vector as well (Ojaveer et al., 2018). Following the reduction of toxic biocidal treatment agents, there has been an increased emphasis on maintaining hull cleanliness (Amara et al., 2018; Lagerström et al., 2018; Ytreberg et al., 2017). Furthermore, shipowners have an economic incentive to keep hulls free of biofouling. A biofouled hull increases a ship's hydrodynamic resistance, which in turn leads to higher fuel consumption (Pagoropoulos et al., 2017).

1.2 Air emissions from maritime transport

The Baltic Sea is one of the most heavily trafficked maritime areas in the world (Helcom, 2018). A substantial volume of maritime traffic is observed between coastal states, including outbound traffic from the Baltic Sea area, such as feeder traffic of container ships to major container ports, such as the Port of Rotterdam (Helcom 2023a, Helcom 2023b). Additionally, the region serves as a key hub for transporting oil products and chemicals (Gritsenko, 2015). A significant number of coastal states rely on maritime transportation. For example, in 2020, about 90% of Finland's imports and 80% of its exports were transported via sea, according to data from Finnish Customs (Finnish Customs, 2020). This share has increased notably in recent years, as trade between Finland and Russia has been significantly reduced due to the war in Ukraine.

The maritime transport sector is responsible for a significant share of global greenhouse gas (GHG) emissions. According to the fourth IMO GHG Study (2020), the sector accounted for 2.89% of all global GHG emissions in 2018. However, maritime transport’s contribution to the pollution load of the Baltic Sea is less significant than that of many other sectors, such as agriculture, industrial, and municipal sources (HELCOM 2023a, HELCOM 2023b). The various types of air emissions from maritime transport require a diverse range of actions to reduce them. The direct proportionality between fuel consumption and CO_2 emissions necessitates reducing consumption levels. Alternatively, the anticipated proliferation of bio- or RFNBO fuels will facilitate a transition from fossil fuels to more climate-resilient alternatives (Chiaramonti et al., 2021). NO_X emissions, a characteristic toxic byproduct of marine diesel engines, have the potential to cause harm to both humans and the environment (Österman & Magnusson, 2013). These emissions can be reduced through improvements in engine technology, the implementation of catalytic converters, or the adoption of lower NO_X-emitting power solutions, such as gas fuels (Spoof-Tuomi & Niemi, 2020). Sulfur in fuel is the main source of SO_X emissions, which are classified as toxic pollutants too. The most effective way to reduce these emissions is to use sulfur-free or at least low-sulfur fuels. While sulfur scrubbers have proven effective in reducing airborne sulfur compounds (Antturi et al., 2016), the broader environmental implications of their use remain under debate (Díaz Delgado et al., 2020; Hermansson et al., 2021; Teuchies et al., 2020). Furthermore, engines emit other emission components such as particulate matter and black carbon. Although not currently regulated by legislation, the impact of black carbon emissions on Arctic warming has been the focus of substantial research in recent years (Chen et al., 2021; Flanner, 2013; Kühn et al., 2020).

Vessels operating year-round in the Baltic Sea are required to be suitable for winter navigation. This requirement has implications for the technical specifications of ships, as well as indirect effects on air emissions. While warmer winters reduce sea ice coverage, colder winters have been shown to extend the ice as far as Gotland, and in some cases, even farther south (Leppäranta & Myrberg, 2009; Meier et al., 2022). The difficulty of ice conditions is not determined solely by temperature; the movement of ice fields can lead to ice packing, which may hinder the navigation of even robust and powerful ships and impose significant physical loads on maritime safety equipment (Löptien & Axell, 2014). Obtaining an ice classification reduces a vessel's energy efficiency, even when operating in open water conditions (Solakivi et al., 2018). Ice classification affects several factors, including required engine power, cargo capacity, permitted structural solutions, and coatings on immersed hull structures (Blanco-Davis et al., 2014; Lindholdt et al. 2015; Oliveira & Granhag, 2020).

Biofouling on immersed hull structures also affects air emissions (Kondratenko et al., 2025). Schultz (2007) presents that increased hydrodynamic drag leads to higher fuel consumption, which in turn raises CO_2 emissions due to the greater thrust power required. SO_X emissions also correlate closely with fuel consumption, depending on the fuel's sulfur content. Significant biofouling can cause engines to operate outside their optimal load range, resulting in elevated NO_X and CO emissions. In vessels equipped with open-loop scrubbers, the increased engine load may also lead to higher volumes of scrubber wastewater.

1.3 Regulations and environmental politics

Over the past two decades, numerous efforts have been made to mitigate the environmental impacts of shipping through various agreements, regulations, and legislation. As outlined in Table 1, regulations issued by the IMO and the EU cover several aspects of environmental management, including air emission reductions, energy efficiency, and biofouling management. These themes are the focus of this thesis.

Table 1. Regulations on maritime traffic related to this topic

Abbreviation	Description	Regulation	Endorsement*
FuelEU Marit.	Fuel GHG Intensity Req.	EC/2023/1805 (EU)	2023/2025
EU ETS	Emission Trading System	EC/2023/957 (EU)	2023/2024
CII	Actual Carbon Intensity	MEPC.328(76) (IMO)	2021/2023
EEXI	Energy Efficiency	MEPC.333(76) (IMO)	2021/2023
SEEMP III	Management Req.	MEPC.328(76) (IMO)	2021/2023
Sulfur limit 0.5%	Fuel Requirement	MEPC.280(70) (IMO)	2008/2016/2020
DCS SEEMP II	Data Collection	MEPC.278(70) (IMO)	2016/2019
MRV	Data Collection	EC/2015/757 (EU)	2015/2018
NECA TIER III	Reg. Fuel Requirement	MEPC.286(71) (IMO)	2017/2019/2021
SECA (0.1%)	Reg. Fuel Requirement	MARPOL Ann.VI (IMO)	1997/2005/2015
SECA (1.0%)	Reg. Fuel Requirement	MARPOL Ann.VI (IMO)	1997/2005/2010
SECA (1.5%)	Reg. Fuel Requirement	MARPOL Ann.VI (IMO)	1997/20052006
Sulfur limit 3.5%	Glob. Fuel Requirement	MARPOL Ann.VI (IMO)	1997/2005/2006
Sulfur limit 4.5%	Glob. Fuel Requirement	MARPOL Ann.VI (IMO)	1997/2005/2006
SEEMP I	Management Req.	MEPC.203(62) (IMO)	2011/2013
EEDI	Energy Efficiency	MEPC.203(62) (IMO)	2011/2013
MARPOL Ann. VI	Air Emissions Regulation	MARPOL Ann.VI (IMO)	1997/2005/2006

* Two years: *approval of regulation and entry into force*; Three years: *approval of regulation, entry into force, and end of transitional period*

The MARPOL Convention (IMO, 1973) sets detailed regulations and obligations for shipping operators to prevent marine pollution. Annex VI (IMO, 1997) specifically addresses air emissions, including the classification of nitrogen oxide emission levels into TIER categories. This convention also forms the basis for the global sulfur limit of 0.5% introduced in 2020, as well as the stricter Baltic Sea sulfur limits of 0.1% since 2015 and the designation of the Baltic Sea as a NECA area in 2021 (IMO, 2017).

The EEDI (IMO, 2013) is a design index for new ships aimed at improving energy efficiency, thereby reducing fuel consumption and emissions. The EEXI (IMO, 2021a) serves as the corresponding index for existing ships. Reducing direct CO_2 emissions from marine engines depends on lowering fuel consumption. The SEEMP (IMO, 2022) regulations provide guidance for shipowners on developing ship operations from an environmental perspective. The MRV Directive (EU 2015/757) establishes monitoring, reporting, and verification requirements for shipping companies, leading to a comprehensive database tracking fuel consumption and CO_2 emissions for vessels operating within the EU. This database will support various applications, including the expansion of the EU Emissions Trading System (EU ETS) to maritime transport in 2024 (EU, 2023a). The Carbon

Intensity Indicator (CII) (IMO, 2021b) assigns an energy efficiency rating to ships. Additionally, the FuelEU Maritime (EU, 2023b) regulation, effective since 2025, mandates shipowners to transition to low- or zero carbon fuels. This regulatory shift is expected to drive significant changes in fuel use within EU maritime transport over the coming decades (Christodoulou & Cullinane, 2022; Cullinane & Yang, 2022; Harahap et al., 2023).

1.4 Sustainability as a multi-criteria decision problem

Sustainability can be defined as the process of achieving a balance among economic, social, and environmental factors to ensure long-term stable development. However, attaining this goal is challenging due to frequent discrepancies between the expectations and actions of the stakeholders involved. Furthermore, identifying sustainable solutions is often challenging. This creates a multi-criteria decision-making problem, for which numerous analytical methodologies exist (Colapinto et al., 2020; Schramm et al., 2020). Wang et al. (2009) provide an in-depth analysis of criteria selection methods used in decision-making processes related to sustainable development in the energy sector. The following multi-criteria decision-making methods are presented: WSM and WPM, categorized as elementary methods: AHP, TOPSIS, Gray relation, and MCDA, classified under unique synthesizing category; and ELECTRE and PROMETHEE, identified as outranking methods.

Huang et al. (2011) state that the selection of methodology depends on the objective of the research project. In the context of strategic decision-making, all the methods considered in their study are collectively regarded as strong. However, TOPSIS has seen a marked increase in its application. While AHP and ANP methods are commonly used in the assessment of environmental impacts, TOPSIS is particularly well suited for sustainable manufacturing. In evaluating air quality and emissions, PROMETHEE stands out as a notably effective method. The literature review by Huang et al. (2011) was extended by Cegan et al. (2017), with the collection of material continuing until 2015. As noted by Cegan et al. (2017), AHP/ANP and MAUT/MAVT methods have become dominant in the field of multi-criteria decision analysis, although studies employing multiple methods have also been published.

A comparative study on multi-criteria decision methods (MAUT, AHP, PROMETHEE, ELECTRE, and DRSA) was carried out by Cinelli et al. (2014). The study revealed that researchers often select methods based on personal experience and familiarity rather than choosing the most suitable approach to solve the research problem. The selection of weighting factors was found to be crucial for achieving sustainable development goals (Pagone et al., 2020; Tarne et al., 2019). Comparative analyses have demonstrated the effectiveness of these methods in life cycle modeling and analyzing incomplete data. In general, multi-criteria decision analysis is an effective approach for evaluating sustainable development processes, although certain aspects can only be addressed by specific methods.

1.5 The objectives of the thesis

The objective of this thesis is to contribute to the sustainable development of the maritime sector by proposing and evaluating two multi-criteria decision analysis models developed during this research. The analysis focuses on air emissions, providing a unifying framework for the four articles (Articles I-IV) included in this thesis. This synthesis presents the application of two models, each based on a distinct theoretical framework, to advance sustainable maritime transport.

The objective of sustainable development of maritime transport depends on implementing solutions that simultaneously address multiple goals, which can be contradictory or synergistic. In an ideal situation, an integrated solution would benefit both operators and the environment. This creates a multi-criteria problem setting, often requiring decisions to be made based on incomplete information or data. This thesis contributes to the ongoing discourse in environmental engineering by analyzing the environmental impact of various technical and operational vessel combinations. The primary focus is on air emissions, along with their trade-offs and synergies with other environmental impacts. This thesis reviews technical emission abatement solutions, utilizes data obtained from on-board emission measurements, employs Bayesian computation, and applies the sustainability index method to identify optimal solutions based on assigned weights.

In Articles I and II, the primary focus is on direct air emissions (tank-to-wake) and indirect emissions (well-to-tank) produced by maritime traffic. These issues are analyzed using the sustainability index method (Iannaccone et al., 2020), which considers greenhouse gas emissions, acidifying and eutrophying air pollutants, emissions harmful to human health, and the operating and investment costs of fuels and emission abatement systems. These impacts constitute a set of evaluation criteria to be applied in various scenarios. The objective of Articles I and II is to introduce an Excel-based modeling tool that allows shipowners and authorities to compare various fuel options (HFO, MGO, LNG) and technical combinations (SCR, WIF, EGR, open- and closed-loop scrubbers) using a comprehensive and illustrative approach to support decision-making. Article I presents the structure of the model, and Article II demonstrates its application to seven virtual ship configurations combining fuel and emissions abatement systems.

Articles III and IV present a multifaceted decision-making problem and present a model for comparing the sustainability of various biofouling management strategies for ships. The model accounts for multiple factors, including the risk of introducing invasive alien species, the ecotoxicological impacts of biocidal hull coatings on marine ecosystems, immersed hull cleaning practices, and the impact of biofouling on fuel consumption and air emissions. My area of responsibility in this research was the on-board measurement of air emissions, including both the collection (Altarriba, 2020a) and analysis (Altarriba, 2020b: Altarriba & Halonen, 2019; Altarriba & Halonen, 2020) of voyage data from vessels operating under real conditions. The analysis employed the Chow-Liu-tree augmented Naïve Bayes method to identify the impact of biofouling on vessel energy consumption (Altarriba, 2020b). This data reinforced earlier findings that biofouling on immersed hull structures leads to a notable increase in fuel consumption and air emissions. The applicability of this work depends on the development of a multi-criteria decision analysis model (MCDAM) based on a Bayesian network analysis technique, as described in Article III.

2 Materials, data and methods

2.1 The analytical model based on a sustainability index

In Articles I and II, the Excel-based sustainability index (Iannaccone et al., 2020) model is presented for the analysis of three fuel options (HFO, MGO, LNG) and five emission abatement systems (SCR, WIF, EGR, OLS and CLS) from a life cycle perspective. In the field of sustainability sciences, life cycle analysis (LCA) represents a prominent approach within the field of design for the environment. It is a key methodology for assessing the environmental impact of products or services (Billatos & Basaly, 1997; Fiksel, 1996; Giudice et al., 2006), particularly in the context of research-oriented development efforts (Ilgin & Gupta, 2010). The objective of this approach is to enhance comprehension of the environmental consequences associated with the product's life cycle, encompassing the utilization of raw materials, manufacturing processes, distribution, actual usage, recycling and disposal (Bovea & Wang, 2003; Bovea & Wang, 2007; Methan & Wang, 2001; Zhang, 2003). The approach has been adapted to support a variety of objectives. In life cycle cost analysis (LCC), the primary objective is to integrate environmental sustainability and production economy considerations (Nakamura & Kondo, 2006). In the context of life-cycle engineering (LCE), the design process, manufacturing, and materials are the subjects of development (Giudice et al., 2006). Life cycle analysis applications based on decision networks are also a viable option, particularly in situations where uncertainty must be considered as part of the process (Zhu & Deshmukh, 2003).

Assessing the environmental impact of renewable fuels necessitates the application of a life cycle approach (Chatzinikolaou & Ventikos, 2015). For instance, the combustion of biofuels leads to the emission of carbon dioxide. However, if the manufacturing process effectively captures a sufficient amount of this gas, net-zero CO_2 emissions can be achieved or closely approximated. This same principle applies to RFNBOs (renewable fuels of non-biological origin). The recently implemented FuelEU Maritime regulation compels shipowners to consider these alternatives. Consequently, researchers are encouraged to develop a comprehensive understanding of the life cycle implications of various options. Bengtsson et al. (2011) and Ma et al. (2012) have published impact assessment results based on well-to-wake analyses of fossil fuels, which have been further supplemented by studies on emission abatement systems presented by Brynolf et al. (2016). As demonstrated by Gilbert et al. (2018), the lifetime emissions of conventional ships are predominantly due to fuel consumption, a principle that also applies to LNG ships (Lindstad & Rialland, 2020).

Evaluating adverse effects throughout the life cycle is inherently a multi-criteria process. Environmental impacts can be assessed from various perspectives. The evaluation of GHG effects is often a subject of interest when attempting to slow down climate change (IMO, 2020; Tatar & Özer, 2018). However, it is imperative to acknowledge that the environment is influenced by a multitude of other types of emissions. The presence of both NO_X compounds and NH_3 has been linked to eutrophication and acidification of the environment, as well as negative impacts on human health (Rathore et al., 2016). Sulfur dioxide (SO_2) is a highly toxic substance (IPCC, 2022). Furthermore, particulate matter has been shown to be especially harmful when inhaled, making its release near settlements, such as ports or coastal areas, particularly concerning (Winnes et al., 2016). However, this issue cannot be addressed solely from an environmental perspective. Alongside environmental sustainability concerns within market-driven economic systems, it is equally crucial to maintain economic sustainability (HELCOM, 2023a; Spoof-Tuomi & Niemi, 2020). Therefore, the chosen business strategies must remain economically viable and sustainable over time.

To address this complex set of interrelated issues, Iannaccone et al. (2020) proposed a sustainability index approach that facilitates the comparison of conflicting aspects. Article I presents a simulation model based on this framework, enabling the evaluation of the life cycle sustainability for three marine fuel solutions (HFO, MGO, LNG) across various emission abatement system combinations, including catalytic converters, sulfur scrubbers, exhaust gas recirculation systems, and water-in-fuel solutions. The objective of the developed model is to provide a user-friendly interface for applying multi-criteria analysis in a variety of cases.

The sustainability index (Iannaccone et al., 2020) consists of two components: an environmental index and an economic index. The environmental index includes four environmental impact categories (potentials): global warming potential over a hundred-year scale (GWP100), acidification potential (AP), eutrophication potential (EP), and human health particulate air potential (HHPA). The economic index is based on the capital and operational costs of the ship, calculated over the selected life cycle. The capital expenditures associated with different powerline systems and fuel alternatives can vary significantly. Fuel consumption over the vessel's life cycle represents often a major cost factor for shipowners. The framework of the sustainability index method is presented in Figure 1.

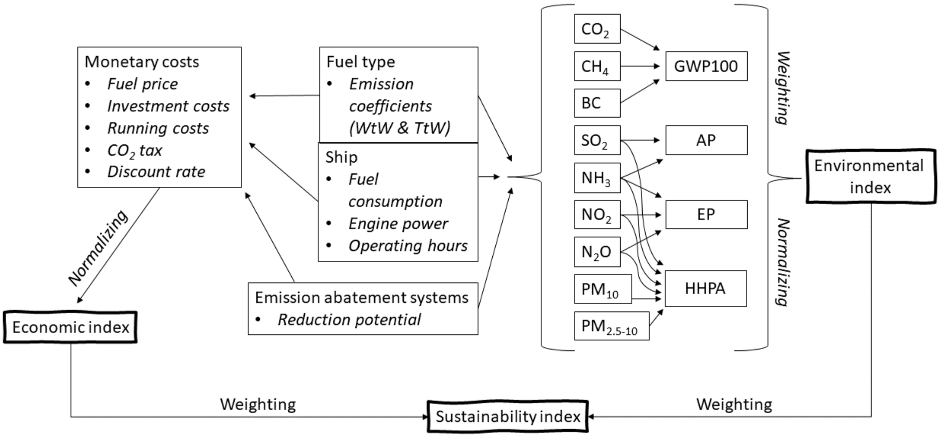


Figure 1. Sustainability index composition (the figure is from Article I)

2.2 On-board data collection

In Articles III and IV, I was responsible for conducting emission measurements, collecting voyage data, and performing subsequent data analyses. Verification of actual emission levels is frequently achieved through on-board emission measurements (Topic et al., 2021; Viana et al., 2020; Winnes et al., 2016). This is particularly relevant for emissions such as NOx, SOx, methane slip (unburned methane emissions), black carbon, and particle matter, which do not correlate directly with fuel consumption in the same way as CO_2 emissions (Jutterström et al., 2021). In addition to emission measurements, obtaining voyage data is crucial for comprehensive analysis. Voyage data can also serve as a set of independent variables in modeling. The model presented in Article I can be applied more effective on a ship-by-ship basis once the emission levels of each individual ship have been defined. The methodology presented in Article I has been validated in our publication (Altarriba et al., 2024), where emissions from the MGO/LNG-fueled ship were measured and the results analyzed using the sustainability index. Article III presents a biofouling management model that requires voyage data as input parameters, including annual operating hours and fuel consumption. These factors directly influence the economic viability of different biofouling management methods from the shipowner's perspective. Furthermore, the conceptual influence diagram presented in Article IV addresses related issues.

The analysis of air emissions from a ship can be conducted through on-board emission measurements, which are then compared with voyage data obtained from ship's systems. This approach aims to assess emission levels under the most authentic operational conditions possible (Jalkanen et al., 2009; Perera & Mo, 2016). In addition to the installed engine and selected fuel type, emission formation is influenced by the ship's operating conditions, particularly the engine load profile. This profile is influenced by various factors, including scheduling, loading, trim, prevailing weather conditions, and performed maintenance (Liu et al., 2020; Wang et al., 2021). In addition to the engine load profile, the efficiency of installed emission abatement systems and their actual performance under operating conditions also affect the prevailing emission levels (Aakko-Saksa et al., 2023; Lindstad et al., 2015; Zannis et al., 2022). However, every measurement process inherently involves some degree of uncertainty (Larjava et al., 1997; Winnes et al., 2016). Storing automatically generated data from engines and other machinery sensors is a prerequisite for analyzing emissions data (Topic et al., 2021). However, this data is subject to system tolerances that can often introduce ambiguities. Data collected by sensors monitoring the ship's movements through water expands the ability to relate measured emission levels to factors such as transport performance or other relevant variables. From a scientific perspective, it is often preferable for researchers to install their own measurement equipment. However, this approach can pose practical challenges and may be declined by the shipowner. Additionally, the analysis process inherently introduces uncertainty. The process is illustrated in Figure 2.

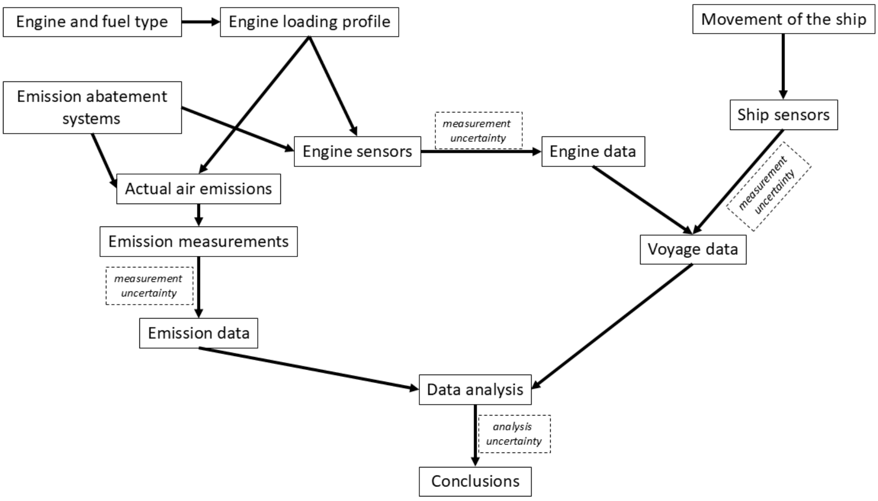


Figure 2. On-board data collection process

Information technology systems have proliferated across a multitude of domains, resulting to the accumulation of vast amounts of data from a wide array of technological systems and entities (Hilbert & López, 2011). As defined by Demchenko et al. (2014), mass data is characterized by a considerable volume of data, often exceeding the capacity of humans to manage it manually. The data variety is extensive and often originates from multiple sources, frequently in unstructured formats. The system's data storage speed is generally high, with the saving process often occurring in real time. The value of data depends on its intended use. While data plays an increasingly important role in various optimization processes, considerable opportunities remain, particularly within maritime transport. Additionally, the veracity of data is crucial in data processing. The analysis of data can also lead to erroneous conclusions regarding entities such as maritime transport, where numerous factors influence the ship's course. While data may not offer a straightforward answer to research questions, it may often contain the necessary information to identify a solution (Emani et al., 2015). This is exemplified by the analysis of the energy consumption impacts of biofouling on immersed hull structures, which formed part of the foundational work during the preparation of Articles III and IV (Altarriba, 2020a; Altarriba & Halonen, 2019; Altarriba & Halonen, 2020).

There is no universally applicable method for storing voyage data for maritime vessels. Instead, solutions must be tailored on a case-by-case basis. The AIS is arguably the most widely recognized standardized voyage data recording system (Yang et al., 2019), used globally on merchant ships. The data recorded by the AIS system primarily tracks the geographical movements of ships, reflecting its original purpose. The system provides time-stamped information on the vessel's position, speed, and course relative to the ground. Additionally, the system transmits vessel identification information, dimensions, and type. However, the system does not record any engine-related information (IMO, 1998).

In the case of older ships, engine systems may still be analog, which limits their capacity to store data digitally (Curley, 2012). For instance, cumulative fuel consumption can be measured using a basic volumetric counter, but such devices do not account for variations in fuel type, temperature, or density. Consequently, this data is manually recorded in the engine logbook. With the introduction of automatic engine control systems, the capability to store data on engine operational parameters has become widely available. However, this data was often confined to the ship's internal systems, and sometimes not recorded consistently even there (Geertsma et al., 2017). On a ship-by-ship basis, significant differences also arose in terms of the data recorded, as well as the capabilities, accuracy, and tolerances of the sensors generating the data. Subsequently, numerous systems were developed to enable real-time monitoring of data over networks, allowing shipping companies to track vessel parameters, such as fuel consumption and other voyage-related information, in real time (Perera & Mo, 2017). However, this information is typically accessible only to the shipowner, resulting in a lack of transparency compared to AIS data, which is publicly available. The utilization of data varies considerably among shipowners. It is common for shipowners to prioritize fuel consumption data. However, they may often overlook the importance and potential insights offered by other types of stored data.

2.3 Biofouling management

Articles III and IV focus on the issue of biofouling management in maritime vessels. The accumulation of organisms on a ship's immersed hull structures increases hydrodynamic resistance, necessitating greater thrust power (Schultz, 2007). This results in increased fuel consumption, leading to elevated air emissions and higher fuel costs. Moreover, a biofouled hull functions as a vector for the dispersal of invasive alien species, facilitating their spread from one region to another (Ojaveer et al., 2018). Aggressive invasive alien species have been identified as posing a significant threat to biodiversity (Pyšek et al., 2020).

The selection of an optimal biofouling management approach requires careful consideration of multiple factors (see Article IV and references therein). Maintaining the cleanliness of immersed hulls using toxic coatings, such as biocidal anti-fouling (or banned TBT) coatings, is a relatively straightforward process. However, these products release toxic substances into the marine environment, resulting in significant biological harm (Ytreberg et al., 2017, Lagerström et al., 2018). Foul-release coatings (non-toxic products that create a slick surface to which biofouling loosely attaches and easily detaches when the ship is in motion) have limited resistance to operation in icy conditions. Consequently, relying solely on these products for biofouling management in ships operating year-round in the northern Baltic Sea is not feasible (Ciriminna et al., 2015). Ice-resistant hard coatings, although more durable in such conditions, will inevitably become fouled over time and require regular in-water cleaning.

In-water cleaning can be conducted in a proactive or reactive manner (Oliveira & Granhag, 2020). During the cleaning process, biological material may be released into the surrounding seawater or collected. The handling of this material significantly influences the risk of spreading invasive alien species. However, it should be noted that employing different cleaning techniques may result in increased cleaning costs, as can the selection of certain hull coatings. Figure 3 provides a summary of the impacts associated with biofouling management.

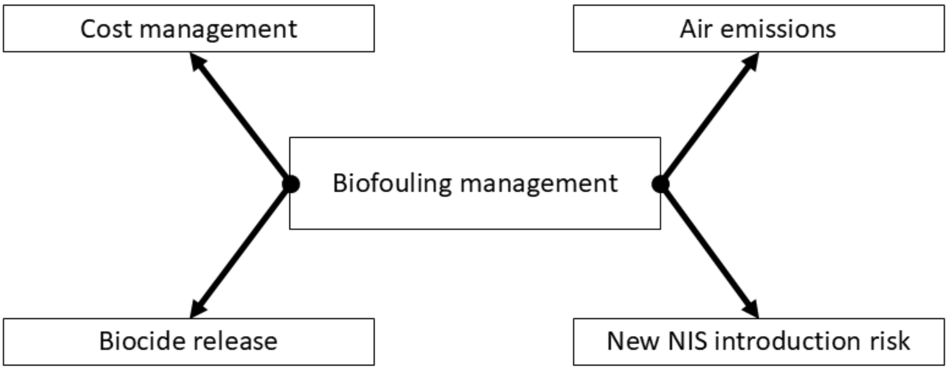


Figure 3. Impacts of biofouling management

As stated in Article IV, certain elements associated with biofouling management are not comparable. Consequently, there has been no effort to draw parallels between them. In Article III, a multi-criteria decision analysis model (MCDAM) based on Bayesian networks (BN) is presented. This model is used to evaluate the sustainability of alternative strategies to control biofouling on ships traversing the Baltic Sea region. The computational probabilistic BN model is based on a CID (conceptual influence diagram) (Article IV), presenting framing and structure of the socio-eco-technological decision problem in question. Biofouling is a significant vector for the spread of invasive alien species, a phenomenon that has often been overlooked in discussions of invasive species spread via ballast waters (Ojaveer et al., 2017; Olenin et al., 2016). In contrast to ballast water treatment, biofouling management has been shown to be beneficial for shipowners (Pagoropoulos et al., 2017). Biofouling of the hull increases the ship's hydrodynamic resistance, leading to increased fuel consumption and air emissions (Lindholdt et al., 2015). Fuel costs represent a significant operational expense, making biofouling management a financially viable proposition for shipowners (Schultz, 2007).

2.4 Qualitative causal and computational Bayesian networks

In Articles III and IV, causal models and Bayesian networks are employed as analytical methodologies. Causal models are frameworks that facilitate the comprehension and representation of causal relationships between variables. The objective is to explicate the influence of one variable on another, thereby facilitating the prediction of interventions. A variety of causal models exist, including, for example, structural equation models (SEM) (Fan et al., 2016), graphical models (DAG) (Ni et al., 2022), causal interference techniques (RCT) (Colnet et al., 2024), and causal influence diagrams (CID) (Jensen & Nielsen, 2007). Causal influence diagrams are visual representations of assumptions about causal relationships and confounding variables. These models can be applied as extension of Bayesian networks in the field of decision analysis. They integrate numerical and graphical components to enable informed decision-making. When combined with probability-based decision-making, powerful tools can be developed to support decision-making under uncertainty (Fahd et al., 2019; Helle et al., 2015; Rahikainen et al., 2014). Bayesian networks are a specific type of probability-based influence diagram. They are distinguished by their computational efficiency, their capacity to identify the most probable explanations, their ability to detect inconsistencies within a system, and their capabilities for sensitivity analysis. This method has been successfully applied to the study of environmental problems (Mäntyniemi et al., 2009; Uusitalo et al., 2007).

A notable characteristic of research on various environmental issues, particularly those of considerable magnitude, is that the applied methodologies often necessitate an indirect approach to examining the object under consideration. The relationships between system-related factors are inherently complex. It should be noted that the results of such analyses, and the conclusions drawn from them, are subject to significant uncertainty (O'Haran, 2012). The application of influence diagrams based on causal models can help illuminate intricate systemic interactions, thereby enabling measurement-based research to be conducted in a more targeted manner.

The Bayesian network model presented in Article III addresses the issue of biofouling management for ships, enabling a comparative analysis of various management methods. Article IV presents a conceptual diagram outlining the interactions between the relevant variables. With regard to air emissions, biofouling constitutes an additional environmental concern: the increase in hydrodynamic resistance, often caused by biofouling, can lead to increased fuel consumption and emissions. In the case of a heavy fouled ship, the difference can be as high as tens of percent (Schultz, 2007). However, at that point, the financial impact becomes so significant that shipowners are generally unwilling to accept such a situation in practice. As fuel prices rise due to new regulations (e.g. FuelEU Maritime and EU ETS), shipowners have strong financial incentives to optimize fuel consumption. In addition, IMO regulations such as SEEMP I-III and CII require ships to maximize energy efficiency in practice.

Following a thorough assessment of both the model presented in Article III and the conceptual influence diagram in Article IV, it was decided to limit the emission output values to CO_2 emissions. The formation of many other types of emissions (e.g. NOx, CO, HC, TVOC) is non-linear with respect to engine load and fuel consumption. This non-linearity can lead to erroneous inferences when such emissions are used in a generic model. Voyage data from multiple ships was analyzed over an extended period, and a total of seven on-board emission measurement sessions were conducted (Altarriba 2020a, Altarriba 2020b, Altarriba & Halonen 2019, Altarriba & Halonen 2020).

2.5 Multi-criteria decision analysis

In many situations, selecting the optimal solution requires balancing conflicting requirements and opportunities. The evaluation of alternatives and influencing factors is frequently accompanied by uncertainty, which can lead to decision-making based on incomplete information. Sustainable development is a dynamic process that aims to achieve a balance among economic, social, and environmental dimensions, often under conditions of limited or uncertain information. Decision analysis comprises a set of methodologies with the following objectives (Cegan et al., 2017; Cinelli et al., 2014; Huang et al., 2011; Wang et al, 2009; Zanghelini et al., 2018):

- To improve understanding of the decision-making context
- To clarify the objectives of decision-making
- To create scenarios that enhance understanding of potential consequences
- To utilize numerical data effectively
- To assist in identifying new opportunities
- To provide a tool for thinking, learning, and dialogue, helping to improve stakeholder understanding and build trust

Decision-making can be conceptualized as either an individual or a collective process. According to Stern et al. (1999), even collective decisions are ultimately made by individuals. Therefore, it is essential for individuals to reflect on their own role within group decision-making. According to Dietz (2003), a good collective decision-making process should meet the following criteria: it should promote the well-being of people and the environment; be based on both facts and values; ensure fairness in both the process and its outcomes; build on human strengths rather than weaknesses; and be understood as an opportunity for learning.

The selection of criteria and the determination of their relative weightings are pivotal elements of multi-criteria decision-making (MCDM) processes. These criteria constitute a set of considerations that are interpreted as indicators of sustainability. They determine how the relative superiority of the alternatives under analysis (in this case, in terms of environmental sustainability) will be assessed. Decision analysis enables the evaluation of options against different criteria, both individually and collectively, making it a well-suited methodological approach for examining sustainability-related issues.

The importance of life cycle analysis is increasing, particularly in the context of renewable fuels. Zanghelini et al. (2018) and Campos-Guzmán et al. (2019) discuss the application of multi-criteria decision analysis in interpreting LCA results, highlighting the wide range of methodological variations within this approach. According to these authors, the most frequently selected criteria are global warming potential (GWP), acidification, eutrophication, economic costs and benefits, social job creation, and occupational safety. In this study, LCA is employed in Articles I and II to assess the comprehensive sustainability of fuel options as part of the sustainability index method. This approach considers emissions affecting global warming (GWP), acidification (AP), eutrophication (EP), and human health particulate air (HHPA) from both well-to-tank and tank-to-wake phases. The same applies to additive consumption in selective catalytic reduction and closed-loop scrubber systems (urea and NaOH).

3 Results

3.1 Multi-criteria sustainability index model (MCSIM) of fuels and emission abatement technologies (Articles I and II)

Article I presents the Excel-based multi-criteria sustainability index model (MCSIM), which is based on the sustainability index method (Iannaccone et al., 2020). The model enables comparison of selected technical and fuel combinations within a single ship. It includes three fuel options (HFO, MGO, and LNG), and users can select emission coefficients for both well-to-tank and tank-to-wake phases. The ship's annual operating profile is modeled by operating hours at sea, in port, and during maneuvering, along with average engine load levels for main and auxiliary engines. Available emission abatement technologies (selective catalytic reduction (SCR), water-in-fuel system (WIF), exhaust gas recirculation (EGR), and two types of sulfur scrubbers (open and closed loop)) can be customized by the user.

The sustainability index method (Iannaccone et al., 2020) comprises environmental and economic indexes, with their relative weightings selectable by the user. The environmental index includes four key impact categories: global warming potential over a 100-year period (GWP100), acidification potential (AP), eutrophication potential (EP), and human health particulate air potential (HHPA). Users can also adjust the weighting among these environmental potentials, allowing for tailored evaluations of environmental impacts across various geographical contexts, such as the high seas, archipelagos, and areas near ports and settlements.

The economic index evaluates the impact of costs on sustainability. While fuel expenses often represent a major cost for shipowners, the model also accounts for investment and operational costs of emission abatement technologies. Substantial uncertainties complicate decision-making regarding future cost structures (Antturi et al., 2016; Cullinane & Yang, 2022). Although various technical options exist (Kondratenko et al., 2025), investment costs require careful consideration. Fuel price volatility and the unpredictability of prices for new fuel types further challenge decision-making (Ferrari et al., 2023). The decision-making process is illustrated in Figure 4, where decision-makers' needs and objectives are shaped by regulations, economic factors, and customer expectations. This process culminates in three main themes: fuel options, emission abatement technologies, and operating profile.

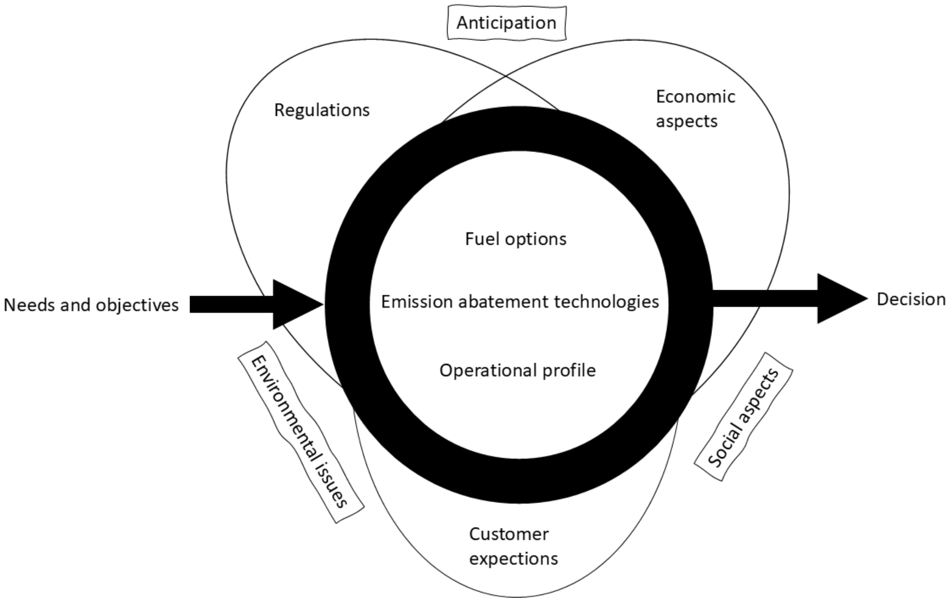
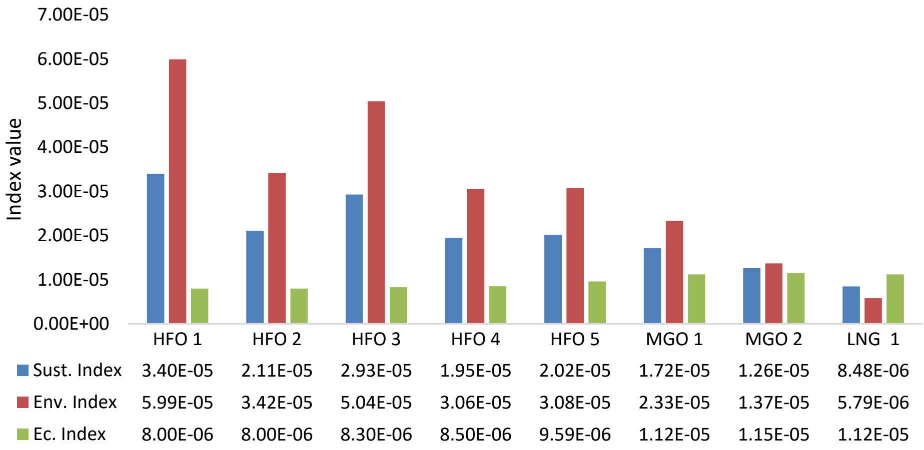


Figure 4. Decision-making process

The sustainability index method used in the MCSIM tool (Articles I and II) offers a practical and adaptable way to compare the overall impact of different fuel and technology combinations. Users can adjust the weightings between economic and environmental indexes, as well as the four environmental impact categories, to reflect various contexts. The model's applicability to analysis is demonstrated through an example in Article I. The fuel sulfur content and emission abatement technologies selected for the scenarios (HFO 1-5, MGO 1-2, and LNG) are listed in Table 2 and the illustrative outcomes are presented in Figure 5. In terms of the sustainability index, values closer to zero are indicative of a more sustainable outcome.

Table 2. Emission abatement technologies and fuel sulfur contents

Scenario	Fuel	SO_2 content	Emission abatement technology
HFO 1	Heavy fuel oil	0.5%	No post-treatment systems (N/A)
HFO 2	Heavy fuel oil	0.1%	No post-treatment systems (N/A)
HFO 3	Heavy fuel oil	0.5%	Selective catalytic reduction (SCR)
HFO 4	Heavy fuel oil	2.5%	Open-loop scrubber (OLS)
HFO 5	Heavy fuel oil	2.5%	Closed-loop scrubber (CLS)
MGO 1	Marine gas oil	0.1%	No post-treatment systems (N/A)
MGO 2	Marine gas oil	0.1%	Selective catalytic reduction (SCR)
LNG 1	Liquefied natural gas	0.0%	No post-treatment systems (N/A)



	HFO 1	HFO 2	HFO 3	HFO 4	HFO 5	MGO 1	MGO 2	LNG 1
🟦 Sust. Index	3.40E-05	2.11E-05	2.93E-05	1.95E-05	2.02E-05	1.72E-05	1.26E-05	8.48E-06
🟥 Env. Index	5.99E-05	3.42E-05	5.04E-05	3.06E-05	3.08E-05	2.33E-05	1.37E-05	5.79E-06
🟩 Ec. Index	8.00E-06	8.00E-06	8.30E-06	8.50E-06	9.59E-06	1.12E-05	1.15E-05	1.12E-05

Figure 5. Sustainability index model results (the figure is from Article I)

A significant number of HFO solutions are associated with unfavorable environmental index values. Conversely, the advantage gained through the economic index is attributable to the lower fuel costs. LNG performs relatively well in this context because LNG has minimal eutrophication (EP), acidification (AP), and human health (HHPA) effects, which are favorable compared to the effects of HFO or MGO options. This is achieved without the necessity for separate emission abatement technology. However, in terms of the GWP100 impact, the benefits are more marginal. While LNG generates fewer CO_2 emissions per unit of fuel burned, the methane slip effectively negates this benefit (Aakko-Saksa et al., 2023). The user can select the size of the methane slip, and as marine engine technology advances, the model can be applied to analyze these situations. The model incorporates black carbon emissions, but further information is required to determine their overall environmental impact. Some studies have indicated that, particularly in the Arctic region, emissions of black carbon can be particularly detrimental (Chen et al., 2021; Flanner, 2013; Kühn et al., 2020).

However, the environmental sustainability of HFO fuels can be enhanced through emission abatement methods. Significant reductions in nitrogen oxide (NOx) emissions can be achieved by installing selective catalytic reduction (SCR) technology (Österman & Magnusson, 2013). Ships that use MGO fuel and are equipped with an SCR system achieve index results that are quite close to LNG. As outlined in Article II, the MCSIM allows for the comparison of other NOx abatement methods as well. Previous nitrogen oxide abatement technologies have included various water-in-fuel solutions (Sun et al., 2022), such as humidification of intake air (HAM) or direct water injection systems (DWI). It is plausible that exhaust gas recirculation (EGR) systems will become more prevalent in marine engine product families soon (Wang et al., 2017).

Investing in a sulfur scrubber system allows vessels to operate with sulfur-rich heavy fuel oil, which is more cost-effective than low-sulfur fuels. Some shipowners in the Baltic Sea region have adopted this solution to comply with environmental regulations (Jonson et al., 2019). The scrubber can be of the open-loop or closed-loop type, and there are also hybrid models with a choice of operating mode. Ensuring sufficient efficiency in open-loop scrubbers necessitates maintaining an adequate alkalinity level in the wash water, which is frequently achieved by employing saline seawater (Andreasen & Mayer, 2007). The hybrid model is a viable solution to tackle this challenge posed by the particularly low water salinity levels in the Baltic Sea, such as in the Gulf of Finland. Marine gas oil (MGO) is a more refined fuel, and the sulfur content of these grades is essentially low. LNG offers the distinct advantage of being virtually sulfur-free, with only a minor amount of pilot oil fuel. When using the MCSIM model, it is also important to consider future fuel trends. In the case of LNG ships, the transition to biogas or synthetic gas is relatively straightforward (Spoof-Tuomi & Niemi, 2020). However, a technologically seamless spread of bio-oils or e-fuels (RFNBOs) is also a potential option within the field of petroleum fuels (Chiaramonti et al., 2021).

3.2 Multi-criteria decision analysis model (MCDAM) for biofouling management (Articles III and IV)

Management of biofouling on immersed hull structures frequently results in financial advantages for shipowners when fuel expenses are reduced (Oliveira & Granhag, 2020). There are several potential strategies for optimizing biofouling management (Luoma et al., 2021). For instance, the necessity for in-water cleaning of coating types varies, and the cleaning interval can be based on proactive or reactive decision-making, which directly affects the outcome of the in-water cleaning process. Implementing a cleaning interval that is too frequent is not economically feasible. However, insufficient cleaning can result in a substantial escalation in fuel expenditures, particularly for hard-coat-treated immersed hulls (Lindholdt et al., 2015; Schultz, 2007). These coatings are widely used on vessels operating in the Baltic Sea region because they are suitable for use in icy conditions. The spread of alien species can be effectively prevented by collecting the biological material released during in-water cleaning (Ojaveer et al., 2017; Ojaveer et al., 2018), although this approach significantly increases the cost of in-water cleaning (Luoma et al., 2021). Figure 6 summarizes the impacts, showing that foul release (FR) coatings effectively prevent biofouling. Self-polishing anti-fouling coatings (SPC) are highly effective but release chemicals. Hard coatings (HC) are non-toxic and suitable for icy conditions but require regular in-water cleaning with or without biomaterial collection.

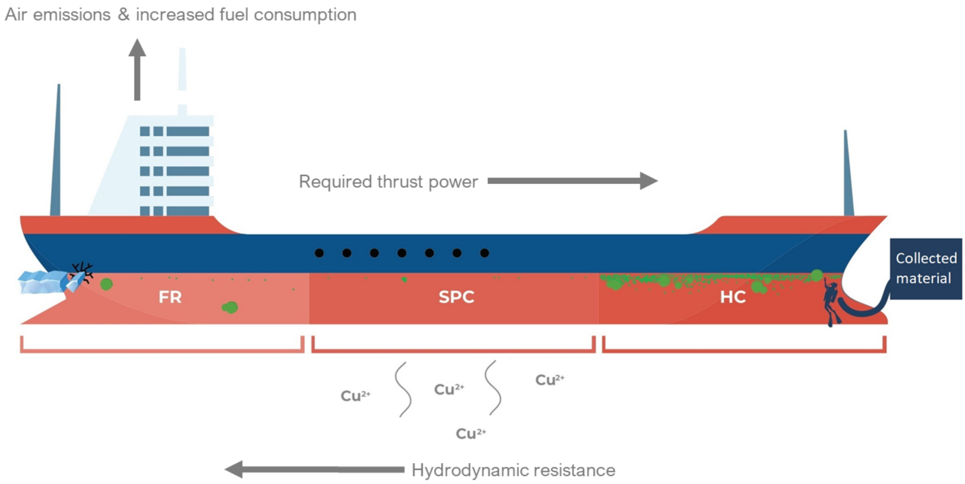


Figure 6. Biofouling on immersed hull structures (the figure is from Article IV)

A substantial amount of research has been conducted on biofouling of immersed hull structures and increased hydrodynamic resistances (Lindholdt et al., 2015; Oliveira & Granhag, 2020). However, the problem is often generalized, with the focus being on the increase in fuel consumption caused by heavily biofouled hulls (Schultz, 2007). Determining the optimal cleaning interval and methodology is a matter of paramount importance for shipowners, as it ultimately guides the decision-making process. In most cases, this decision must be made at the level of individual ships and routes. My contributions to Articles III and IV focus on the ship's energy consumption and the impact of biofouling on it, including on-board emission measurements and voyage data collection and analysis. Additionally, I conducted research on the properties of various coating materials and the implementation of in-water cleaning methods. For additional information, please refer to the following publications: Altarriba (2020a), Altarriba (2020b), Altarriba & Halonen (2019), and Altarriba & Halonen (2020).

In Article IV, a developed conceptual influence diagram (CID) is presented (Figure 7). This CID is a visual model that summarizes the multi-criteria problem setting related to biofouling management. The CID diagram consists of decision variables (rectangles), change variables (ovals), utility variables (diamonds), and conditional dependencies (arrows) between them. Decision nodes (rectangles) include the selection of hull coating type, coating renewal interval, in-water cleaning interval and method, and compliance with regulations. The change variables (ovals) are divided into ecosphere (green ovals) and technosphere (blue ovals) nodes. The ecosphere is comprised of several factors, including sediment copper concentration, time of the year, potential for NIS introductions, total biofouling mass per ship, biofouling level, natural environmental conditions, species assemblage, attachment of organisms and growth of organisms. The technosphere factors that must be taken into account include the physical and chemical conditions of the substrates, copper release to the ecosystem, hydrodynamic forces, shipping routes, niche areas, hull form, hull structures, wet surface area, hull dimensions, ship type and size, idle time, operation hours, hydrodynamic resistance, fuel consumption, fuel type and price, and cruising speed. The utility variables (diamonds) are divided into two categories: costs (orange diamonds) and environmental impacts (purple diamonds). The cost category includes fuel, coating, and IWC expenses. The environmental impacts consist of NIS introductions, emissions, and ecotoxicological effects.

Figure 7. Conceptual influence diagram (CID) of biofouling, from Article IV

The developed MCDAM model (Article III) and CID diagram (Article IV) provide an opportunity to enhance the comprehension of the collective impact of selected alternatives and combinations. The MCDAM model structure is presented in Figure 8. As with the CID diagram, the MCDAM model consists of decision variables (rectangles), chance variables (ovals), utility variables (diamonds), and conditional dependencies (arrows) between them. The decision variables are classified into four categories: orange rectangles indicate coating-related variables, red ones indicate shipping-related variables, blue ones indicate in-water cleaning-related variables, and green ones indicate operational profile-related variables. The white ovals represent probabilistic random variables (chance nodes). Utility variables consist of costs (yellow diamonds) and environmental impacts (green diamonds). The model assists users in attaining a holistic understanding of the biofouling management consequences, which is advantageous to public authorities, researchers, as well as representatives of shipowners (Luoma et al., 2021). In the ideal scenario, outcomes that benefit both the environment and the economy can be identified, as outlined in Article III (e.g., in the Baltic Sea region, the use of hard coat type coatings with regular immersed hull cleanings).

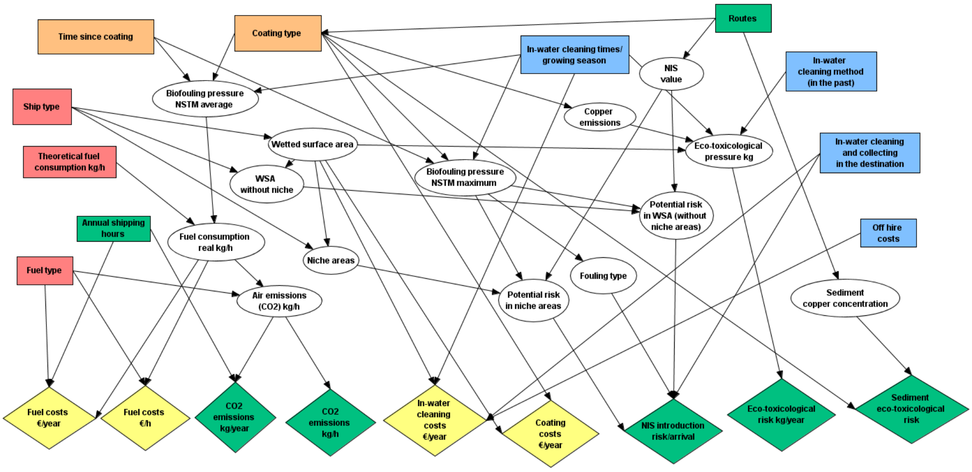


Figure 8. Multi-criteria decision analysis model (MCDAM), from Article III

As outlined in Table 1 of Article III, a comprehensive list of the input values utilized in the model scenarios is provided, while Table 2 in Article III presents a detailed summary of the modeling results. The study's findings provide a comparative analysis of various biofouling management methodologies across different routes. The scenarios vary depending on the selected method of immersed hull structure treatment, which may include a hard coat, a biocidal anti-fouling agent, or a foul-release coating. The in-water cleaning processes may involve one of the following: no cleaning, cleaning at a specified interval, or the collection of released biological waste. As demonstrated in Table 2 of Article III, the implementation of a non-biocidal hard coat, in conjunction with routine in-water cleaning procedures and the collection of released biological waste, has proven to be an effective biofouling management strategy for vessels operating in the Baltic Sea region. In the Southern Baltic, under completely ice-free conditions, foul-release coatings also provide satisfactory results.

4 Discussion

4.1 Comparison of the approaches

In this thesis, I have analyzed air emissions produced by shipping and have evaluated the sustainability of the potential solutions to reduce them. To achieve this objective, two decision analysis models have been developed. The MCSIM model allows for the assessment of air emissions from various technological and fuel configurations of a vessel, utilizing the sustainability index method outlined in Articles I and II. The MCDAM model allows for the examination of vessels' energy and emission efficiency as part of the search for sustainable hull biofouling management strategies, using Bayesian networks as the analytical method (Article III). In the development of the MCDAM model, a conceptual influence diagram (CID) model was first created to understand and describe the structure and framing of the multi-criteria management problem at hand (Article IV). As outlined in Table 3, the strengths of these decision-analytical approaches (MCSIM and MCDAM) are detailed, with the CID model serving as a point of reference.

Table 3. Comparison of strengths of the MCSIM, MCDAM and CID models

Model **Method** **Articles**	**MCSIM** **SusI**[1] **I & II**	**MCDAM** **Bayes**[2] **III**	**CID** **ID**[3] **IV**
Improved understanding of the management problem	+	+	++
Numerical comparison of options	++	++	-
Graphical illustration of impacts	-	+	++
Deterministic outputs (point estimates)	++	-	-
Probabilistic outputs (distributions)	-	++	-
Aggregated outcome (optimizable)	++	-	-
Non-aggregated outcome (transparent)	-	++	-
Considers the impact mechanisms of decisions	-	+	++
Considers the impact magnitudes of decisions	++	+	-
Stakeholder collaboration (building trust)	+	+	+

++ = A clear strength of the model
+ = A strength of the model
- = N/A

1 = Sustainability index
2 = Bayesian network
3 = Influence diagram

The MCSIM and MCDAM models facilitate a comprehensive understanding of the management problems studied. The CID model employs a visual representation of the system to illustrate the mechanisms that generate the diverse impacts of the decisions on the target variables (i.e., assessment endpoints). This approach provides the end user with a visual and comprehensible interface. The CID model is not dependent on the available numerical data, which allows for the examination of interactions between different factors independently of this limitation. This is evident in the simplifications that were necessary when the CID model (Article IV) was implemented as the foundation for developing the MCDAM model (Article III).

Numerical data is frequently used to support decision-making processes, offering a quantitative approach to problem-solving by providing a basis for solutions that are quantifiable. The MCSIM model (Article I) is based on a deterministic approach to data management for inputs, weights, and normalization factors, as well as outputs. This approach is selected (Article II) because the input data formats obtained by end-users in the maritime sector are frequently available in this form (e.g., fuel consumption, fuel price, operating hours, etc.).

The normalization of the MCSIM model determines the relative magnitude of the indicator of the impact category under investigation in relation to the reference data (as well as the environmental impact categories and the economic indicator). For the environmental impact categories, the normalization factor utilizes the indicator-specific emissions of the European Union member states, and the economic indicator is normalized in relation to the gross domestic product of the European OECD area (Laurent et al., 2013). When implementing the method, particularly in other geographical areas and to a certain extent within Europe, it is crucial to ascertain that the suitability of the selected normalization factors is appropriate in relation to the designated reference framework.

The MCDAM model (Article III) is based on Bayesian networks, which represent data as distributions, capturing dispersion and uncertainty. Unlike the MCSIM model, which aggregates different environmental impacts into weighted index values to enable comparison, the MCDAM avoids summarizing diverse outcomes into a single index. This approach prevents the loss of information and addresses the problem of non-uniform impacts, such as those from global warming, pollution, or health effects caused, e.g., by sulfur emissions or fine particles. Considering economic factors further complicates the assessment, as it introduces additional dimensions to the decision-making process. While aggregated indexes are common in society for simplifying complex data, the MCDAM model's strength lies in assessing multiple outcomes in parallel without assuming commensurability, thus providing a more nuanced analysis of environmental and economic trade-offs.

4.2 Applicability of the methods

The MCSIM and MCDAM models are both appropriate for examining the consequences of decisions, although there are differences in emphasis. A report on the applicability of the MCDAM model (Luoma et al., 2021) highlights its strengths in terms of a holistic understanding of the system studied. However, the model's interface and usability could be improved, particularly for users like shipowners who require clear and straightforward analytical solutions. In this sense, to my mind, the MCSIM could be applied more straightforwardly if the aim is to have end-users, e.g., representatives of shipowners or public authorities, benefit from it (Articles I and II). However, when selecting input values, particularly those related to the well-to-tank phase and weighting factors, an inexperienced user may inadvertently obtain results that appear reliable but are, in fact, biased. Significant variations in well-to-tank factors have been observed, particularly in the case of renewable fuels (Bengtsson et al., 2011; Campos-Guzmán et al., 2019; Chiaramonti et al., 2021; Harahap et al., 2023).

In the context of weight factors, Rowley et al. (2012) presents a range of approaches to the selection process. However, they underscore the significance of case comprehension and the implementation of general instructions that are challenging to apply. Furthermore, Tarne et al. (2018) note that a broad distribution without clear clustering is typically observed when weightings are selected. According to them, the analyst's own perspective and attitude often significantly impact the selection of weighting factors. An analyst who emphasizes sustainability typically underscores the significance of environmental factors, while a non-sustainability analyst often places greater emphasis on economic implications. Pagone et al. (2020) have proposed a solution to this challenge, in which these shortcomings have been reduced by automatic weighting. This method is based on an ordinal combinatorial criterion of four pre-defined weight distributions. When planning the further development needs of the MCSIM model, the selection methods of weighting factors are an important development target.

The MCSIM model has been developed for the purpose of comparing alternative options for managing air emissions from shipping and observing the effects of different choices on them. The transition to non-fossil fuels will fundamentally transform the entire system. Most emissions related to fossil fuels occur during the tank-to-wake stage (Chatzinikolaou & Ventikos, 2015), and the harmful effects of these emissions are well documented (Aakko-Saksa et al., 2023). The situation regarding non-fossil fuels is more complex (Bengtsson et al., 2011; Campos-Guzmán et al., 2019; Chatzinikolaou & Ventikos, 2015; Gilbert et al., 2018). For a significant proportion of the presented fuel options (e.g., e-fuels, biofuels, methanol, or ammonia), it has been determined that the emissions from the well-to-tank phase have a more substantial impact and may play an integral role in determining the actual sustainability of the option in question.

Current emissions reduction policies place a strong emphasis on maritime greenhouse gas emissions to slow climate change (EC/2023/959; EC/2023/1805; IMO, 1997; IMO, 2017; IMO, 2021b; IMO, 2022). However, when considering sustainable development, it is essential to determine the total emissions of the option over its life cycle (well-to-wake), especially when discussing renewable or synthetic fuels. It is also important to consider non-GHG emissions. For instance, Rathore et al. (2016) and Singh and Agrawal (2008) have demonstrated that acidification and eutrophication caused, for example, by emissions of sulfur or nitrogen oxides, have the potential to destroy natural habitats for various species. The health impacts of these emissions, such as particulate matter or black carbon, depend on the geographical area where they are released (Geels et al., 2021). The MCSIM model assists end-users in perceiving and comparing the life-cycle emissions of alternative solutions. Holistic (multi-criteria) analysis models are instrumental in facilitating development in a manner that ensures the implementation of investments or other changes does not result in the transfer of environmental problems or climate issues to other thematic areas. Green transition and sustainable development are processes that share the common goal of both mitigating climate change and protecting ecosystems.

The MCDAM model presented in Article III emphasizes biofouling management. While the primary research objective of biofouling management is to prevent the spread of non-indigenous species, it also offers economic benefits to shipowners by enhancing the vessels' energy efficiency and reducing fuel consumption (Lindholdt et al., 2015; Oliveira & Granhag, 2020; Schultz, 2007). This incentivizes shipowners to comply with regulations, such as the SEEMP, while also encouraging economic considerations. This is exemplified by the probable increase in fuel costs due to the transition to alternative fuels and the supplementary costs associated with the emissions trading system. The MCDAM model is advantageous for shipowners because it provides concrete and numerical data on the economic impact of biofouling management. This information encourages the management of the risk of new invasive species introductions. In contrast to the automatic fuel consumption optimization applications included in many modern on-board control systems, the MCDAM model allows for a comprehensive study of the entire system. This includes factors such as in-water cleaning methods, forms of emissions (air emissions, sediment eco-toxicological emissions), risks associated with the introduction of non-indigenous species (NIS), and the financial implications of these factors.

These models (MCDAM and MCSIM) can also be approached from a complementary perspective. The MCDAM model can be utilized to assess the environmental impacts of biofouling management methods in terms of both fuel consumption and other environmental impacts (such as NIS introduction risks or eco-toxicological impacts). Once changes in fuel consumption are defined, the

MCSIM model can be employed to examine the environmental impacts of air emissions on a wider scale. This analysis has the potential to expand beyond the scope of the CO_2 emissions considered in the MCDAM model to encompass the capabilities offered by emission abatement systems for managing emissions. Additionally, the MCSIM model can consider the life-cycle emissions of fuels, a critical aspect during the transition from fossil fuels to alternative solutions (Bengtsson et al., 2011). During this transition, there is a notable increase in the significance of examining emission levels during the well-to-wake phase (Chatzinikolaou & Ventikos, 2015).

4.3 Limitations of applicability

The models presented in this thesis offer a framework for enhancing stakeholders' understanding and recognition of the implications of various choices and the systemic mechanisms through which choices impact target variables. This enhancement in knowledge and understanding will contribute to informed decision-making by both maritime stakeholders and decision-makers in society. However, it is essential that users understand both the capabilities and limitations of the models (Colapinto et al., 2020; Fan et al., 2016), as misuse or misinterpretation may lead to flawed judgments or incorrect conclusions.

Environmental modeling relies on the use of deterministic models, and the assessment of the uncertainty of the results of these models is an essential component of the application process (Uusitalo et al., 2015). If the model structure and calculation logic are based on a deterministic data set, as is the case with the MCSIM model, reasonable accuracy can be achieved when simulating constant navigation routes with an operation profile where load variations both during and between voyages are minimal. When analyzing navigation routes that include significant changes in operational profile, the inclusion of probabilities is justified, as the averaged input values often lose accuracy (O'Hagan, 2012). One approach to address this challenge, or a potential solution, could involve integrating the model over time and selected variables. However, it should be noted that this approach is not directly supported by the current model design.

The principle of averaging of input values is also partly related to the choice of the weighting coefficients of the MCSIM model. Weighting factors can be used to shift the analysis between different environmental impact types in the case of the environmental index, or alternatively between environmental resilience and economic sustainability in the case of the sustainability index. Weighting is designed to enable users to effortlessly generate diverse perspectives on the results generated by the model (Iannaccone et al., 2020). For instance, the level of harmfulness of emissions to human health is significantly higher in ports or near settlements than in high sea conditions (Berregard et al., 1999; Geels et al., 2021).

Furthermore, studies have shown that shallow brackish water basins, such as the Baltic Sea, are more susceptible to acidification or eutrophication compared to the oceans (Antturi et al., 2016; Leppäranta & Myrberg, 2009; Rathore et al., 2016; Singh & Agrawal, 2008). However, it is crucial to acknowledge that the application of weighting is a subjective decision (Iannaccone et al., 2020; Pagone et al., 2020; Tarne et al., 2019). Misuse of this model, whether intentional or otherwise, can result in outcomes that appear to be "sustainable".

Sustainability assessment is relatively straightforward for fossil fuels, as most emissions occur during end use (Aakko-Saksa et al., 2023; Chatzinikolaou & Ventikos, 2015). For renewable fuels, the evaluation is more complex due to emissions being distributed more evenly across the life cycle (Gilbert et al., 2018; Tanhuanpää et al., 2024). The reliability of data collection is contingent on the fuel production method, though it can also present significant challenges, particularly in terms of identifying multiplier effects, e.g., LULUCF impacts (van der Hilst et al., 2018; Savaresi et al., 2020). The regional variation in emission impacts challenges the validity of using average values for both emission and weighting factors (Barregard et al., 1999; Jutterström et al., 2021; Tatar & Özer, 2018; Viana et al., 2014). This analogous trend is also evident in the MCDAM model, where some of the input values are subject to a degree of speculative estimation, in addition to the collection of quantifiable data. A notable illustration of this is the NIS introduction risk (Leppäranta & Myrberg, 2009; Molnar et al., 2008), which is characterized by the difficulty in obtaining unequivocal measured data. This affects the model's applicability, as stakeholders typically expect clear answers to questions like "What exactly should I do?", "Why?", and "What will it cost?" This issue emerged in our stakeholder interviews (Luoma et al., 2021).

The models discussed in this thesis facilitate the simulation of complex problems related to air emissions and biofouling. According to the findings in Articles I-II, it is essential to consider the life cycle emissions of fuels when assessing the environmental sustainability of a technical combination, especially in the context of renewable fuels. Due to the complexity of sustainability assessment (Colapinto et al., 2020; Shrivastava & Berger, 2010) and the necessity of a multi-criteria approach (Campos-Guzmán et al., 2019; Cinelli et al., 2014), methods such as the sustainability index (Iannaccone et al., 2020) are employed to comprehensively assess factors that would otherwise be challenging to compare. According to the findings of Articles III and IV, I state that despite the rising adoption of automated fuel consumption optimization systems (including numerical monitoring of biofouling levels), holistic models such as those outlined in Article III remain paramount in addressing the multifaceted challenges posed by biofouling (Lindholdt et al., 2015; Oliveira & Granhag, 2020; Schultz, 2007). Both models support decision-making, whether in preparing legislation or identifying and evaluating new solutions in practice.

5 Conclusions

The thesis is composed of four articles that examine the environmental impact of shipping, particularly regarding air emissions. The first two Articles (I and II) present the model (MCSIM), which enables multi-criteria analysis of air emissions from shipping based on the sustainability index method. The method facilitates the execution of a life cycle analysis of the selected emission abatement methods and fuel type combinations. The sustainability index method presents results in aggregated form, thereby enabling the index-based comparison of otherwise difficult-to-compare items. However, this approach also has a key limitation: index methods inherently simplify data, which can result in information loss.

Article III presents the MCDAM model, which is based on a Bayesian network. This model can be applied when analyzing the consequences of selected biofouling management strategies. Article IV presents a conceptual influence diagram, which is utilized in the development process of the MCDAM model. The MCDAM model presents results in the form of probability distributions. The model allows for parallel examinations of different categories of results in a non-aggregated manner. Due to the inherent complexity of the biofouling issue, the numerical representation for certain input values and results is considered an educated estimate.

The MCSIM model demonstrates that liquefied natural gas consistently achieves more favorable index values in comparison to heavy fuel oil and marine gas oil fuels. This is primarily due to its low sulfur and nitrogen oxide emissions. Conversely, the model demonstrates that reducing fuel sulfur content and implementing catalytic converters can markedly decrease emissions from oil fuels. However, the MCSIM method is most advantageous when analyzing renewable fuels, as life-cycle emissions frequently play a pivotal role in evaluating the overall sustainability of alternative fuel options.

The MCDAM model suggests that the use of non-toxic, hard coatings capable of resisting the ice conditions in the Baltic Sea, combined with regular immersed hull in-water cleaning (every 3-4 weeks), can lead to a scenario where costs, biofouling levels, and the resulting increase in fuel consumption are all kept at acceptable levels. In the southern Baltic Sea, foul-release type coatings may also be appropriate under ice-free conditions.

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