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Transport, Infrastructure and Logistics

Advancing Sustainability on Heavy-Lift Vessels: Reducing Greenhouse Gas Emissions

A Techno-Economic Decision Support System for Retrofitting

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"Limitations are only Perceptions"

Anders Hofman, 2019
(The only one ever to complete an IRONMAN on Antarctica)

Executive summary

Problem statement

Global warming is an undeniable crisis that demands urgent action. The increasing frequency and severity of disasters—such as extreme weather events, rising sea levels, and biodiversity loss—clearly demonstrate its impact. These disasters do not only affect vulnerable communities but also disrupt global economies, ecosystems, and overall planetary stability. Addressing this challenge is no longer optional; it is a shared responsibility that requires collective action to build a sustainable future.

Greenhouse gases (GHG) trap heat in the earth's atmosphere, contributing to climate change. The maritime industry accounts for 3% of human-caused GHG emissions, drawing specific attention from the EU (European Union) and IMO (International Maritime Organisation), which have introduced regulations to reduce these emissions. Since EU regulations also carry financial consequences, commercial shipping companies now have an added incentive to cut their emissions to remain financially viable. While significant research exists on emission reduction strategies, it remains unclear which factors are most important in such decisions. Moreover, no research to date has focused on decarbonizing the heavy-lift shipping sector.

Heavy-lift vessels (HLV) differ from other ocean-going ships due to their changing destinations, which make it infeasible to build supporting infrastructure in fixed locations. Additionally, HLV require maximum free deck space to accommodate a wide range of heavy-lift operations. These unique challenges have not been addressed in existing studies. This thesis aims to fill that gap by focusing on the following central research question:

Which technological innovations are best suited for heavy-lift vessels in alignment with the objectives of Jumbo Maritime, the EU, and the IMO for reducing greenhouse gas emissions?

Scope

The study focuses on building a Decision Support System (DSS) for selecting GHG emission eduction technologies on existing HLV, while maintaining financial viability for the shipping company. Expensive retrofits, such as replacing engines for alternative fuels (like hydrogen and methanol) were excluded, as these are feasible only for newbuild vessels in the case of Jumbo Maritime due to budget constraints. The study specifically tailored criteria for HLV with its specific characteristics. The focus has also been on GHG emissions since these are the most relevant in the regulations of the IMO and EU, making the to-be-developed Decision Support System (DSS) applicable to these. This DSS aims at giving a solid base into what GHG decreasing measure is best to implement aboard HLV, considering the criteria of Jumbo Maritime. The HLV Fairmaster, a vessel owned and operated by Jumbo Maritime, was used as a case study to populate and use the DSS.

Methodology

In this multi-method research, the process towards answering the research question has been divided in four steps:

1. Information gathering
   To structure the research problem, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is conducted, as can be read in section 1, which incorporates insights from the external maritime expert DNV, from literature review, and from Jumbo Maritime. Next, the developed DSS needs three key inputs:

   - Regulations, identifying EU and IMO directives through a literature review;
   - Alternative measures, gathered from literature and industry sources;
   - Decision criteria, determined via interviews with relevant departments at Jumbo Maritime.

   These steps establish the foundation for selecting and evaluating sustainable measures and determine the playing field on which this thesis is based.

2. Building the DSS
   The Decision Support System (DSS) is developed by constructing a performance matrix that evaluates how different alternatives perform based on the identified criteria. To weigh the criteria reliably and consistently, a Multi-Criteria Decision Method (MCDM) has been applied. The MCDM used is the Best-Worst Method (BWM), which incorporates the identified criteria in a structured interview, where

Jumbo Maritime's Board of Directors assigns relative preferences to determine their importance. This structured approach not only enhances the quality of decision-making but also helps organizations make better-informed and more defensible choices. An advantage of the method is that its pairwise comparison framework reduces decision-makers' mental effort. Additionally, a case-study on the HLV Fairmaster provides vessel-specific operational data, making sure the DSS accounts for real-world constraints.

3. Verification and Validation
   To ensure the DSS produces reliable and logical results, a sensitivity analysis and verification tests have been performed. These validate whether the DSS accurately represents decision-making trade-offs and verifies its robustness under different scenarios, such as changes in fuel prices, regulatory shifts, and variations in fuel efficiency performance.

4. Output Interpretation
   The DSS output is translated into economic insights to support decision-making. A Marginal Abatement Cost Curve (MACC) is used to assess the cost-effectiveness of each measure, identifying the most impactful and financially viable solutions. This ensures that the final recommendations align with Jumbo Maritime's strategic goals, balancing sustainability with financial feasibility.

Main findings

Current state of the regulations regarding reducing GHG emissions

The IMO and EU regulations have a shared objective which is to decarbonize maritime transport by becoming net-zero in GHG emissions in 2050.
They both have intermediate milestones in order to achieve this. These has been described extensively in sections 2.3 and 2.4 respectively.
The EU has the Emission Trading Scheme (ETS), which has become extended to shipping in 2024; FuelEU, which sets a limit on the GHG intensity of vessels, active from 2025; and MRV, used for reporting of GHG emissions from vessels, from 2018. Companies like Jumbo Maritime also have to report on their sustainability goals and activities with the Corporate Sustainability Reporting Directive (CSRD).
The IMO also has initiatives but there does not exist a standardized enforcement mechanism for vessels with lower ratings or non-compliance. These are the Carbon Intensity Indicator (CII), a rating system calculated on the amount of grams of CO2 emitted per cargo-carrying capacity and nautical mile, active since 2023; the Energy Efficiency Existing/Design Index EEXI/EEDI, which is a benchmark on the energy efficiency of a (new build) vessel, also from 2023; the Ship Energy Efficiency Management Plan (SEEMP), which entails a management plan and for report data in the IMO Data Collection System (DCS) for energy efficiency.
Important to note is that HLV are excluded from the scope of CII and EEXI for now. The expectation is however that the IMO will introduce financial penalties (similar to the EU regulations) near the end of the decade. But, individual port states can potentially restrict the access or give other kinds of penalties.

Possible measures for HLV to decrease their GHG emission

From a longlist of GHG emission reduction technologies for maritime shipping in general, eight measures have been shown to be potential candidates for their implementation on HLV.

- Wind-Assisted Ship Propulsion (WASP), which are mechanical suction sails that work by dragging air across an aerodynamic surface (a foil) to generate lift. This results in propulsive efficiency, reducing fuel consumption, OPEX and GHG emission.
- Wavefoil, which is a retractable foil that is installed on the bow of a vessel. These generate additional thrust due to the up-and-down motion of waves.
- Air Lubrication System (ALS), which reduces significant resistance by creating a layer of airbubbles between the ship's hull and the water.
- Hull cleaning, which is a machine that cleans the hull of a vessel of fouling, reducing the resistance of the hull. This has to happen multiple times a year.
- Flipper Zipper, which is an object that is places in the rails on the side of the vessel. This rails generates friction when sailing but these are needed when lifting heavy object due to stability reasons.

- Propeller Boss Cap Fins, this is a cap with fins, which is rotating with the propellor on the post-swirl side. It transforms the leaving rotational energy into effective thrust.
- Eco-control, this is a measure that uses slow-steaming (lowering the speed) and a variable pitch setting to decrease emissions. This trade-off is optimized in software;
- Heat recovery, this is using exhaust gasses to warm up thermal oil which is then directed to installations which need that warmth, leaving auxiliary engine obsolete in some cases.

Relevant criteria

Through semi-structured interviews with relevant department managers and structured interviews with the board members, the following key criteria and its corresponding score were identified:

Criterion	Weight
ROI	42%
Operational flexibility	24%
Installation time	8%
Operational profile	13%
CRI	11%

ROI emerged as the most important factor, as financial viability and a shorter payback period are critical for decision-making. A measure will not be implemented if it does not have a strong positive business case. Operational flexibility is also seen as important, since alternatives may not interfere significantly with essential vessel functions such as crane operations or free deck space. Installation time is another key factor, with modifications ideally scheduled during drydock to avoid costly delays. Measures should also align with the vessel's operational profile, considering unpredictable routes and varying loads to maximize efficiency and emission reductions. TRL is essential to confirm that the technology is proven and reliable before implementation. Since TRL is a classification criteria, Commercial Readiness Index (CRI) has been used instead. These are scores that start from being commercially proven (1) until widely implemented (6).

Classification criteria

As stated, there are classification criteria that GHG emission reduction measures have to pass to be potential solutions for Jumbo Maritime. These are safety, regulatory compliance, TRL and maximum CAPEX ($<$ 1 million EUR).
Safety is particularly crucial to Jumbo Maritime, seen its Stay Well program which shows its role as a fundamental company value; next, the measures have to reduce the GHG emission of a vessel which is the scope of this thesis; then, they have to be proven technologies since Jumbo Maritime does not want to experiment in commercial operations from a safety and financial risk perspective; and a maximum CAPEX of 1 million EUR is set. From a longlist, depicted in appendix A.10, this shorter list with the eight technologies listed above has been made, based on these classification criteria. Lastly, reputation is gaining importance, as clients and employees increasingly value environmental responsible companies. However, it was not yet considered a significant factor in the selection process.

Outcome DSS

The DSS identified Propeller Boss Cap Fins (PBCF) as the best alternative for implementation aboard HLV. It is a low-hanging fruit, offering significant benefits with minimal drawbacks. This conclusion is supported by results from the Marginal Abatement Cost Curve (MACC), verification tests with varied inputs, sensitivity analyses on different variables, and the case-study on the HLV Fairmaster. Across all analyses, PBCF consistently ranked among the top alternatives, often scoring above 9. Furthermore, it has a low CAPEX of around 150 000 EUR and low OPEX of approximately 5 000 EUR per year, mainly for routine maintenance of the propeller cap. It delivers significant fuel savings, resulting in a ROI of about one year. Additionally, it scores highly in operational flexibility, as it does not interfere with onboard processes, and has a short installation time of just one day, which can even be done underwater. Since it does not negatively impact the operational profile and is a proven technology with a high CRI, it stands out as the most practical and efficient choice.

The DSS showed that other measures like Hull cleaning and Eco-control are promising solutions, but each has its limitations. In addition, the sensitivity analysis and verification tests confirm that the DSS shows to give reliable and logical rankings.

Recommendations

The motivation to become more sustainable lies first in financial incentives, which are the ETS and FuelEU penalties and potential IMO financial penalties in the future. This is also reflected in the high weight (42%) that board members give to the financial criterion. Further, motivation lies in being regulatory compliant to the EU and IMO with regard to report their emissions (EU MRV & IMO DCS). These require companies to report emissions and outline reduction plans. And lastly, which becomes increasingly important: reputation and market pressure. Clients, financiers, and employees prefer companies with strong sustainability commitments.

Decarbonisation roadmap

During the process of doing this research, it became apparent that the answer to the main research question is more difficult than simply investigating how the criteria are valued. To navigate the increasingly stringent IMO and EU regulations targeting net-zero GHG emissions in shipping by 2050, shipping companies must develop a clear and structured decarbonisation roadmap. This roadmap should outline clear milestones, reduction targets, and strategy decisions, ensuring compliance while optimizing investment in emission reduction measures. Given mandatory reporting requirements such as IMO DCS, EU MRV, and CSRD, companies must align their strategies with evolving policies, while also preparing for financial mechanisms like ETS and FuelEU penalties. A well-structured roadmap should use the DSS and the MACC to prioritize effective measures based on cost and reduction potential. Additionally, creating a digital operational profile (using IMO and EU reporting data) can improve decision-making by making sure that the most appropriate specific decarbonisation measures are applied to the individual vessels.

To achieve these reduction targets, Jumbo Maritime should consider a mix of technological and operational strategies. A specific amount of decreasing GHG can be achieved by implementing a specific kind of alternative. WASP is the best decision when a large reduction is desired, since the MACC shows that this has the greatest amount of decreasing potential. Or the other way around, if a small reduction is wanted for a low price, the Flipper Zipper can be the best decision. It depends on what the strategy is. PBCF showed to be the most promising solution overall. Furthermore, companies should take advantage of FuelEU reward factors, such as WASP discounts on GHG intensity (up to 5%), RFNBO incentives (halving GHG intensity calculations for 2025-2032) and onshore power exemptions. Pooling mechanisms also offer flexibility by allowing surplus reductions from compliant vessels to compensate emissions from others in the same pool. By integrating these strategies within the decarbonisation roadmap, shipping companies can ensure long-term compliance, optimize costs, and proactively position themselves for a net-zero future.

Key strategic decisions

- Assigning whether vessels are going to sail in the EEA (European Economic Area) or not, to optimize the division of regulatory penalties. If some vessels emit far less emission, it would be wise to focus those ships on jobs within the EEA.
- Look into FuelEU reward factors, which have a strong reduction potential resulting in significantly lowering the FuelEU penalty.
- Exploring pooling with other vessels to balance emissions within the group.
- Considering biofuels and other sustainable fuels, despite their higher costs, in order to comply to the EU regulations. Passing on these extra costs to the customer has to be taken into consideration.

Main Recommendations

1. Install Propeller Boss Cap Fins for improved efficiency.
2. Develop a structured decarbonisation roadmap with milestones until 2050.
3. Create a digital operational profile for smarter fleet management. This also makes the operation of the Eco-control more efficient.
4. Utilize shore power where available to minimize emissions (supported by FuelEU incentives)

Limitations and assumptions

This research has several limitations that define its scope and limits, ensuring transparency and reliability. Firstly, the scope which is specified on existing HLV and technological measures that decrease GHG emission. Regarding criteria scoring, most scores (except ROI) were based on literature research and manufacturer data, which may not fully represent real-world vessel performance. Operational flexibility scores were influenced by manufacturer claims, which could be biased, while installation time estimates depended on available case studies, making actual values potentially variable. Operational profile was simplified, as accurately modeling route-specific factors like wind conditions and fuel availability was beyond the research scope. The CRI (Commercial Readiness Index) was also literature-based but could evolve as new technologies gain market traction. Several assumptions were made to align the study with practical constraints, like aggregating fuel-saving percentages across different fuel types, capping maximum CAPEX at 1 million EUR, and excluding subsidies from the model. Additionally, the case-study data that has been used was based on the past few years, and a discount rate of 5% was applied. The ROI (payback period) threshold was set at 20 years, ensuring feasibility for existing vessels, and reputation effects were excluded based on stakeholder feedback but recognized as a future consideration. These limitations provide essential context for interpreting results, reinforcing the need for a structured decision-making framework in HLV decarbonization.

Risk on bias

The DSS is designed to reduce cognitive and motivational biases and enhance decision-making by being transparent. This is its key feature, hence the reason why it is built in a transparent tool, namely Microsoft Excel: it is not a black box. Transparency ensures that inputs, weights, and results are clear and objective. To obtain unbiased weights, board members were interviewed separately and asked only about their trade-offs between criteria, which were identified through interviews with department managers. By using the structured Best-Worst Method (which is a Multi-Criteria Decision Method), unfair weighting was prevented, while relying on objective (hard) data such as CAPEX, OPEX, and fuel savings minimizes personal or organizational influence. However, some inputs were acquired directly from manufacturers, which is a risk of confirmation bias. Since inputs can be adjusted, the DSS remains flexible and avoids overconfidence in initial estimates. This approach ensures that the DSS is a fair, reliable and trustworthy tool for decision-making.

Final remark

Becoming future-proof is more than just financial success. Although financial health is important, it is only one part of the bigger picture. A company must also aim to be a leader in the energy transition and build resilience against future challenges. Reputation is leading in this, which is known across the managers of Jumbo Maritime, as seen in the interviews, but which is not adopted by them yet. Limitations are perceptions: what seems like a barrier is often just a mindset. The key is to recognize which challenges truly matter and "choose your battles wisely".

Figure 1: HLV Fairmaster in action

Contents

Nomenclature

AHP	= Analytic Hierarchy Process
AIS	= Automated Identification System
ALS	= Air Lubrication System
BWM	= Best-Worst Method
CAPEX	= Capital Expenditures
CCS	= Carbon Capture and Storage
CEO	= Chief Executive Officer
CFO	= Chief Financial Officer
CH4	= Methane (GHG)
CII	= Carbon Intensity Indicator
COO	= Chief Operational Officer (or operational director)
CO2	= Carbon dioxide (GHG)
CO2-eq	= CO2-equivalent (GHG)
CRI	= Commercial Readiness Index
CSRD	= (EU's) Corporate Sustainability Reporting Directive (regulation)
DCS	= IMO Data Collection System (regulation)
DP2	= Dynamic Positioning, level 2
DSS	= Decision Support System
EC	= European Commission
ECA	= Emission Control Areas (regulation)
EEA	= European Economic Area
EEDI	= Energy Efficiency Design Index
EEXI	= Energy Efficiency Existing Ship Index
EGCS	= Exhaust Gas Cleaning System
EPRIB	= Emergency Position-Indicating Radio Beacon
ESG	= Environmental, Social and Governance
ESRS	= European Sustainability Reporting Standards
ETS	= European Union Emissions Trading System (regulation)
EU	= European Union
FEUM	= FuelEU Maritime (regulation)
GHG	= Greenhouse gas (emission)
GT	= Gross Tonnage (intern volume of a vessel)
HFO	= Heavy Fuel Oil (3,5% sulfur m/m)
HLV	= Heavy Lift Vessel
ICCT	= International Council on Clean Transportation
IMO	= International Maritime Organization
LNG	= Liquefied Natural Gas
MARPOL	= Maritime Pollution (convention by IMO)
MCDM	= Multi-Criteria Decision Method
MEPC	= Marine Environment Protection Committee
MGO	= Marine Gas Oil (<0,10% sulfur m/m)
MRV	= Monitoring, Reporting and Verification (regulation)
MT	= Metric tons (unit)
NOx	= Nitrogen oxides (not GHG)
N20	= Nitrous oxide (GHG)
OPEX	= Operational Expenditures
PBCF	= Propeller Boss Cap Fins
PM	= Particulate Matter (not GHG)
PSSA	= Particularly Sensitive Sea Areas
SEEMP	= Ship Energy Efficiency Management Plan
SOLAS	= Safety of Life at Sea
SOx	= Sulfur oxides (not GHG)
TRL	= Technological Readiness Level
VLSFO	= Very Low Sulfur Fuel Oil (<0,50 sulfur m/m)
WASP	= Wind-Assisted Ship Propulsion

1 Introduction

The global average temperature for the most recent 10-year period, from 2014 to 2023, is estimated to be the warmest 10-year period on record, at around 1.2°C above the 1850-1900 average. This extreme heat causes the greatest mortality of all extreme weather, with an estimated 489 000 heat-related deaths per year between 2000 and 2019 (WMO, 2023). Resulting from this, it must be stated that climate change is no longer a future problem. More massive consequences are happening, such as the melting of the Antarctic. It is expected that before 2050 the Arctic Ocean will be completely ice-free in late summer if nothing is done to diminish this. Consequence of this is a rise of the sea level and this can be as much as 2 meters in a high-emissions scenario. Hurricanes will become stronger and more frequent as well due to the climate warming (NASA, 2023).
Much more consequences can be stated but in this thesis, there will be solely scoped onto the emissions by the maritime sector, which plays a significant role in climate change. The dominant maritime shipping sector is responsible for nearly 3% of human-caused CO2 emissions in 2018 and roughly 11% of life-cycle transportation CO2 emissions in 2020 (ICCT, 2022). Close to 90% of the world's goods rely on maritime transportation (Khan et al., 2021) and due to the expected increase of demand, global shipping increases (Hennessey, 2024). It has reached an all-time high in May 2024, leading to severe port congestion. The port congestion and the unavailability of more containers, leads ultimately to incredible spot rates. Trade disruptions also can have a very significant effect on the global trade and its prices. Currently (September 2024) there are attacks on ships in the Red Sea, which leads to ships, which are sailing between Asia and Europe (including ships from Jumbo Maritime), having to sail all the way around Africa. This change in routing from the Suez Canal (Red Sea) to the Cape of Good Hope (Africa) increases the delivery times by 10 days or more on average, impacting companies and economies. The longer distances result in a 70% increase in GHG emissions for a round trip from Singapore to Northern Europe (UNCTAD, 2024). The effect is significant due to the fact that 15% of global maritime trade uses this route (IMF, 2024). TEU-miles (miles traveled by containers worldwide) have increased by 17.9% globally in 2024 compared to the same period in 2023 and this is mostly driven by these Red Sea diversions to Africa. This increase of shipping leads logically to a substantial increase of emission. These examples show the relevance of the influence of the maritime industry on global warming.

To tackle this problem of rising emission, the EU (European Union) and the IMO (International Maritime Organization) have generated different approaches. The IMO has the directive to be net-zero in greenhouse gas (GHG) emissions by 2050 which is in line with the Paris Agreement. This has been decided in the 80th session of the Marine Environment Protection Committee (MEPC). They also made indicative check-up points to be at least 20% (striving for 30%) by 2030 and to be at least 70% (striving for 80%) by 2040. This will be counted with a Carbon Intensity Indicator (CII), which gets stricter each year with the reference year 2019. This directive is binding for companies and it aims at improving the efficiency of vessels. The EU has the Fit-for-55 directive to have 55% less GHG emissions by 2030 with the help of ETS, which are emission certificates, and FuelEU Maritime, which sets limits for the yearly average GHG intensity for a vessel above the 5000GT. Its regulations ultimately aim at becoming net-zero on GHG emission in 2050 as well. These are described in section 2.

1.1 Jumbo Maritime

Jumbo Maritime is a global shipping company that is specialized in heavy-lift and next to that, they also offer offshore transportation and installation solutions. Currently, Jumbo Maritime sails with eight vessels, which are also depicted in appendix A.5. Two vessels of Jumbo Maritime are equipped with two deep water cranes which can lift up to 900 tons and a dynamic positioning system (DP2), which lets them combine shipping with offshore installation services. Next, all the vessels are equipped with cranes with a lifting capacity as much as 3000 tons for working with the heavy load, which ranges from transporting tugboats to wind turbines, see figure 2a and 2b.
In their operations, they sail around the whole world and with traveling all these distances, a great deal of GHG emission gets released into the air. In order to reduce that emission, different technologies can play a part. Especially on long distances, eg. Rotterdam - Singapore, big improvements can be made with technological innovations regarding sustainability. But already, there have been efforts by Jumbo Maritime to decrease their carbon footprint. Very recently (2024) for example, mechanical sails (Ventofoils by Econowind) has been fitted aboard one of their vessels, namely the HLV Jubilee.
Currently, there are a lot of technical innovations available that can be used to make the maritime fleet more sustainable in order to satisfy the goals of the IMO and the EU. In this thesis, there is examined which of these innovations is best fitting for the HLV Fairmaster, a heavy-lift vessel of Jumbo Maritime which will be taken as reference-input for the developed decision support system (DSS). However, a combination of different

(a) Shipping wind turbine foundations

(b) Shipping tugboats

Figure 2: Uncontainerized cargo (pictures owned by Jumbo Maritime)

innovations is also possible. Combined with this initial set of alternative innovations, the constraints/ requirements of Jumbo Maritime have to be taken into consideration. This is what Jumbo Maritime values as most important in such a recommendation, which can include aspects like vision, budget, preference etc.

1.2 Objectives

Jumbo Maritime has stated in their latest yearly overview (the so-called Townhall 2024) that it needs to be on top of the rules and regulations regarding emission reduction, especially now it is changing a lot. As stated, in 2024 the EU and the IMO have both intensified their efforts to regulate GHG emissions. But in the process towards choosing a measure that decreases the GHG emission of a vessel, it is unclear what needs to be considered. This is a highly complex problem because it is unclear what factors are most important in such a decision, especially given the wide range of available measures to reduce GHG emissions on existing vessels where each of those vessels has their own operational profile. The structure towards this implementation is missing.
These are the reasons why Jumbo Maritime values this thesis. The ultimate goal is to future-proof the company and maintain its position as a key player in the maritime heavy-lift market. To achieve this, a multi-disciplinary approach is required which goes into decision-making while using the technological impact of the different measures and the specific profile of the heavy-lift sector. Consequently, the following primary objectives have been identified in collaboration with Jumbo Maritime:

- Finding the best sustainable measure that reduces GHG emission aboard HLV. The best sustainable measure is calculated by taking the relevant criteria into account, such as the amount of GHG emission that it decreases, the financial consequences and more. Trade-offs are be made between these criteria and the HLV Fairmaster, a vessel of Jumbo Maritime, is chosen as initial input for the DSS. The DSS can be used for all kinds of vessels, changing the input is enough.
- Giving a clear overview on the different regulations on GHG emission which are put into action by the EU and the IMO and how they are connected. This will help the Jumbo Maritime to understand the current state of these directives and determine the playing field for choosing the right GHG decreasing measure. Although the EU regulations are leading in this research, it is necessary to have a overview of all the relevant regulations of the IMO and EU since they can become important in the future. The regulation overview can also be used for goals like considerations in ship building, next to being future-proof.
- Describing the different alternative measures which are possible to be implemented on HLV. These measures are selected, based on several characteristics, like if they reduce the GHG emission of vessels, how expensive they are, what the current state of them is (technological readiness), and their implications. Only the relevant alternatives for Jumbo Maritime's HLV are taken into account. This depends on the scope: it only takes the existing vessels (+ their current engines) into consideration.
- Getting insight into which criteria Jumbo Maritime values as most important for making decisions regarding measures that decrease GHG emissions which can be implemented aboard their vessels. Different departments have to be interviewed and their input must be used in the consideration of the board of directors of what is important. In this way, all the relevant departments within Jumbo Maritime are heard and it is known what they value as important;

- Most importantly: Developing a framework by combining the elements above into a structured DSS for implementing sustainable measures on vessels. This framework has to include some kind of transparent tool which gives an output on which alternative is valued as most promising when implemented. In this way, it is known what has to be considered when implementing a GHG decreasing measure. By having this framework, a structure will be become to exist, which now is still missing within Jumbo Maritime. Due to this, it is unknown what has to be considered when wanting to implement an innovation.

1.3 Scope

The scope of this research focuses on identifying potential measures to reduce GHG emissions on HLV to ensure compliance with the goals of the IMO, EU and Jumbo Maritime. These measures may include upgrading onboard hardware, adopting new technologies, and using alternative fuels that are compatible with existing engines. The study is limited to solutions that use current engines, as Jumbo Maritime has determined that retrofitting or replacing engines is financially unfeasible and therefore outside the scope of this research. The primary objective of this thesis is to develop a DSS that helps to determine which measures to implement considering the criteria of the relevant stakeholders. These criteria are identified through interviews and subsequently weighted based on their relative importance. The focus is specifically on HLV and how different emission reduction measures perform against these criteria. Jumbo Maritime serves as a reference case for implementing emission reduction measures aboard its HLV, but the DSS is designed to be applicable to other maritime organizations, as it incorporates various input factors.

To establish a comprehensive framework, the research examines regulations focusing on the GHG emissions in the maritime sector, both within the EU and globally. EU regulations such as FuelEU Maritime (FEUM), the Emissions Trading System (ETS), and the Monitoring, Reporting, and Verification (MRV) system play a key role in compliance, depending on the operational range of the vessels. Vessels operating outside the EU do not have to comply to these regulations, whereas EU-bound ships must adhere to them. Although IMO directives are non-binding and currently lack financial penalties, their global influence suggests they may implement stricter regulations in the future that align with EU regulations. Therefore, IMO directives are also considered in this research to ensure a complete analysis.

To validate the applicability of the decision support tool, the research employs a case study of Jumbo Maritime's HLV Fairmaster. While the DSS is adaptable to different vessel types with varying operational profiles, the study specifically focuses on ocean-going heavy-lift vessels that sail long distances, as Jumbo Maritime's fleet consists of these, making them relevant. In contrast, offshore vessels that remain stationary using Dynamic Positioning (DP) systems, for example, would not benefit from certain emission reduction technologies like Air Lubrication Systems (ALS). As a result, the scope of this thesis is limited to the heavy-lift shipping sector.

The DSS is particularly valuable in addressing criteria that are difficult to quantify in monetary terms, allowing for a more comprehensive decision-making process. The necessary data is gathered from literature and through interviews with a diverse range of stakeholders. These stakeholders include external organizations such as DNV, as well as different departments within Jumbo Maritime, including commerce and operations. By integrating various perspectives, the DSS ensures that the recommended measures align with both regulatory requirements and operational feasibility.

1.4 Relevance of thesis

GHG emission reduction is becoming an increasingly important topic, especially in the maritime sector. Regulations from the EU and IMO are getting stricter each year, making it essential for companies like Jumbo Maritime to reduce their carbon footprint. To stay competitive and attractive to clients, Jumbo Maritime needs a structured approach to lowering emissions. While past initiatives have successfully reduced GHG emissions aboard vessels, these were isolated breakthroughs without an established framework. A clear structure is missing in the implementation process, making it difficult to consistently apply effective measures.

To meet these regulations, various technologies can reduce GHG emissions from ships. However, the effectiveness of a technology depends on factors such as vessel characteristics and operational profile. Selecting the best solution requires considering multiple parameters and perspectives from different stakeholders. This highlights the need for a Decision Support System (DSS): a structured and transparent multi-criteria approach to selecting the most effective GHG reduction technologies.

Beyond technology selection, this thesis explores sustainability in the maritime sector and provides an overview of relevant regulations. This helps clarify what is possible and what factors need to be considered when implementing emission reduction measures. The entire maritime industry is struggling to comply with evolving regulations, and frameworks like the one developed in this thesis make it easier to define the right criteria. These criteria have been gathered through interviews with different departments within Jumbo Maritime, each with its own priorities and objectives. Given the broad scope of this topic, the research takes an exploratory approach. Transparency is key in this framework to ensure stakeholder acceptance and prevent bias. Finally, different regulations are analyzed and used to assess the effectiveness of various GHG reduction measures.

1.5 SWOT analysis

It is clear that the emission needs to be reduced by the maritime sector since it plays such a significant impact on climate change. However, the challenge lies in the uncertainty of how this can be effectively achieved. So, first the problem needs to become clear, since it is still unstructured. This is where the SWOT analysis comes in: it gives structure to the problem by providing a comprehensive framework to evaluate the key factors which influence the current situation. Below, the SWOT analysis is explained, followed by the outcome of the analysis.
SWOT stands for Strengths, Weaknesses, Opportunities, Threats. It is a technique that can be used for multiple ends, and one of these is assessing the potential of a business, or a part of that business (Kenton, 2024). In this thesis, this is the assessing of potential alternatives that makes the HLV more sustainable. In order to assess which one this is, the problem has to be structured and it must be clear what has to be done. This is where SWOT analysis comes into play. This SWOT analysis is scoped on the relevance of implementing sustainable measures and the requirements they must comply with. It can be divided into four quadrants which structure the positive and negative aspects in the internal and external dimension, as can be seen in figure 3. The input for the internal dimension comes from their website but mainly from conversations and the interviews (see appendix B). The input for the external dimension comes from literature research and the DNV, see chapter 4.3.

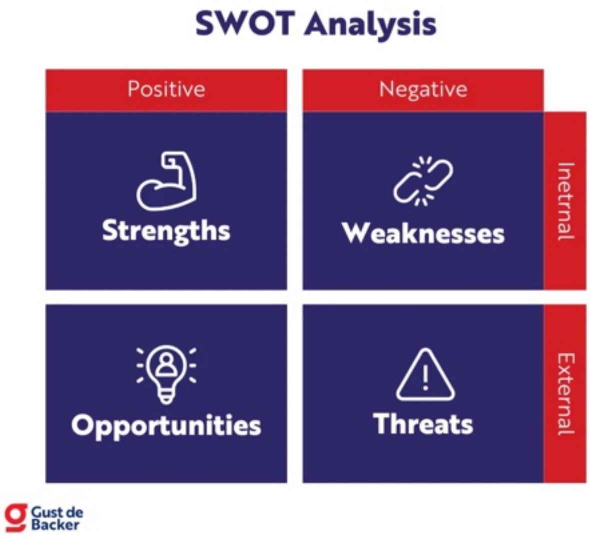

Figure 3: SWOT analysis (De Backer, 2024)

1.5.1 Strengths

The Strengths are what is working well within the company. Within Jumbo Maritime this consists, firstly, of safety. They have an internal safety awareness program called "Stay Well" which lets it operate to the highest safety standards. They state: "Safety awareness is part of our DNA, enabling us to identify and mitigate risk. Our in-house “Stay Well” program, exceeds the requirements of the latest regulations and is a solid foundation for our safety driven culture." (JumboMaritime, 2024). Examples of this is that every employee, even at the office needs to follow a physical course on the safety policy of Jumbo Maritime, on the rules and to develop a base of safety knowledge. When you arrive at their office for the first time, you are also permitted to watch a video on safety at the building and that you have to always hold the railing when using the stairs.

Next to safety, Jumbo Maritime also excels in engineering and then specifically in heavy-lifting. It is a company with a history: in 1968 their first vessel called "Stellaprima" set sail with four, 12-ton derricks (cranes). This was a remarkable innovation for that time and from that moment on, they became a pioneer in the heavy-lift shipping industry. They keep investing in the latest state-of-the-art engineering methods, software and equipment. Within heavy-lift shipping there is a obvious need for custom and careful planning, which comes down to the smallest detail. This is vital for the success of the job due to the heaviness of the job and when it goes wrong, it really goes wrong. The HLV Fairmaster, for example, has 2 Huisman cranes which each can lift up to 1500 tons. And to make sure the cargo is transported safely and efficiently, Jumbo Maritime carries out a great deal of detailed preparatory work. With advanced software, "such as 2D and 3D AutoCAD systems, Orcaflex and Safetrans and are equipped to make finite element calculations and structural and ship motion analyses. On request we can prepare 3D animations to visualise the stowage and lifting operations." (JumboMaritime, 2022).

Furthermore, Jumbo Maritime also characterizes itself with strong client relationships. This results in a distinct way of putting themselves in the market and heavy-lift jobs that keep coming in from known contractors. The reliability of Jumbo Maritime lets them be a attractable player and due to the fact that they keep innovating, it is aiming to stay that way. In 2011, they started the Jumbo Innovation Program which has two goals. Firstly to develop innovative transport and installation solutions and secondly to continuously advance Jumbo's safety, reliability and cost effectiveness.

In conclusion, Jumbo Maritime's main strengths are safety, engineering skills and strong client relationships. These three factors are key to successfully adopting sustainable innovations. Firstly safety, it is important because it ensures that new measures can be used without risk to the crew, to the vessels and to the environment. A strong safety focus also gives confidence to all stakeholders by that these changes won't introduce new dangers. Secondly. engineering expertise helps the company to develop and apply new measures that reduce fuel use, lower emissions and improve overall efficiency. And lastly, client relationships are also important because they ensure support for new changes. Clients trust and prefer companies that are reliable and forward-thinking to being future-proof, so Jumbo Maritime's good reputation makes it easier to gain customer support for sustainable changes.

Overall, these strengths give Jumbo Maritime a solid foundation for bringing in sustainable innovations, helping the company stay competitive while reducing its environmental impact.

1.5.2 Weaknesses

They have been innovating with the Jumbo Innovation Program but specifically adapting sustainable measures has been left behind. Due to the limited attention that this program got, it was canceled. Initiatives of reducing the amount of emission were becoming more popular, but they never really came of the ground. From numerous conversations with the Fleet Managers of Jumbo Maritime and the interviews (appendix B), it became clear that the barriers towards sustainable innovations came down to three aspects: time, decisiveness and budget. With time, the time of the vessels is meant: their planning in dock is full. This time is fully booked for maintenance tasks and other changes to the ships. When changes have to be done to the vessels, time is needed in order to let them be implemented safely and successfully. But time also came down to the time of the Fleet Managers: their time is already fully booked with day-to-day tasks of managing the vessels. If they also have to analyze which innovation to test, they cannot complete all their tasks in time. Another organization which is specialized in this matter, has to be hired, but then, decisiveness and budget come into play again.

Next, decisiveness: it has been shown in the past years that innovations rarely break through. Initial tests have been done with different innovations, such as the Flipper Zipper (see 3.2.3), but then there was just stopped with the further implementation. They have been designed, a safety manual A.3 has been made, they have been constructed, they have been tested, but they did not work optimally. The design was slightly off and after redesigning and re-manufacturing, they were not used anymore. There has to be said at that point to find out what is wrong and continue until they are fine tuned and there is worked with them successfully. So in short, decisiveness comes down to the missing coordination regarding the question which alternative to implement. There has to be a system or force which lets innovations to be implemented through: a structure. For this structure to work, there needs to be a clear emission reduction goal and a set budget to reach it. When this exists, different business cases can be set up which aim at reaching that goal by using that budget.

Bringing us to the last aspect: budget. This one is pretty straightforward, there has to be budget for the

implementation of new innovations. Often, the budget is too small for sustainability. This might change in the upcoming years due to the pressure of the regulations but the past has shown that sustainability is ranking rather low on the budget list.
In short, the main problems (time, decisiveness, and budget) are barriers in the implementation of sustainable innovations. However, recently some steps have been made, like the mechanical sails on the Jubilee and special hull coatings, but these efforts are limited. For example, the sails are only leased, not bought for permanent use. Another example is that preparations were made on the HLV Kinetic for a kite, but when finally a budget became available, the manufacturing company of the kite was out of business.

1.5.3 Opportunities

Opportunities lay ahead. As said, there are many alternatives that can be implemented and since the drive of the maritime sector towards becoming more sustainable has been rather late, a lot is possible. A lot of companies have emerged which develop innovations that decrease GHG emission and also the other sectors have developed. Also, since some alternatives have been implemented on other vessels of Jumbo Maritime, the effect can be studied and used appropriately. Next, what also creates opportunities, is the fact that the topic of sustainability is so popular. Regulations from the EU and initiatives from the IMO create strong incentives for the maritime industry to innovate and reduce GHG emissions.

In an interview with DNV, shown in B.7, and in their paper "Energy Transition Outlook 2024, Maritime Forecast 2050" (DNV, 2024a), shows that there are multiple opportunities for the maritime sector in reducing their GHG emission. They can be summed up in three points:

- Operational and Technical energy efficiency measures, which reduces fuel consumption. In chapter 3, eight of them are described which are used in this thesis. Another one, digitalization, has not been used but DNV has referred to them (also in their interview) as very promising. Digitalization can be used for optimizing the routes and calculating the right speed for arriving just in time. In this way, the optimal powerbalance can be achieved which results in a minimal GHG emission while still arriving in time. Thus, the real-time monitoring tools help track fuel use and engine efficiency. The computer states for example that the vessel is going to fast and that it can slow down (slow-steaming effect), and the depth of the water can be used when sailing between islands, resulting in a optimal sailing pattern in terms of energy use. Using digital technologies, the maritime industry can also collect and analyze data to improve how ships perform. Digitalization and AI are also used in different sectors (like the automobile industry, look at Tesla), so why not extend their use towards the maritime sector? Lastly, digitalization can also be used to predict when to schedule maintenance. When sailing through tropical oceans, more fouling can get attached to the hull, resulting in less energy efficiency. By keeping in track how much fouling will get attached by monitoring the operational profile, this can be prevented.
- Alternative fuels, transitioning to carbon-neutral fuels is crucial for long-term decarbonisation. The alternative fuels get increasingly more attention due to it being essential in a zero-carbon 2050. However, DNV notes that the availability of these fuels is severely limited, which shows a focus on energy efficiency and other strategies until supply increases. When the availability and the infrastructure is existing though at the ports though, it will become profitable to use alternative fuels. This is also the ultimate aim of the FEUM regulation.
- Carbon capture to secure a carbon-neutral fuel usage. Key ports to develop the carbon capture and storage capacity and infrastructure that it needs. But since carbon capture is out of the scope of this research, as described in 3.5.2, this does not get additional attention.

1.5.4 Threats

Externally, threats exist which pushes the maritime world to becoming more sustainable. The financial threats come from the EU regulation penalties. The EU regulations have set a certain capacity for emission of the maritime sector which consists of the FEUM policy and the EU's ETS policy. These policies are described in the chapter 2.2. Summarizing, FEUM requires shipping companies to gradually reduce the carbon intensity of the fuels they use, aiming for a strong shift toward low-carbon and renewable alternatives over the coming decades. Also a penalty exists which is designed in such a way that no advantage can exist from accepting the fine when sailing into the EU and doing jobs while exceeding the GHG intensity. Then, ETS is a regulation which works with a cap-and-trade principle which means it has a maximum of emission certificates. The number of certificates represents how much you can legally emit. Logically, if you emit less then the number of certificates you own, you can sell and vice versa. MRV is a system which demands a certain way of reporting the emissions, and is used for the ETS calculation. The IMO also has regulations but these are not financial such as the EU regulations are. However, these (like the CII) can lead to operational restrictions or other actions imposed by flag states. They are designed to make an incentive to make the ships more sustainable and these incentives have to be stated in the SEEMP, the Ship Energy Efficiency Management Plan.

Moreover, the technology needed to make ships more energy-efficient, like hybrid propulsion engines, is costly and takes time to install. Many shipping companies, especially smaller ones, may struggle to afford these upgrades, which may lead to higher operating costs and thus increased freight rates. Achieving the IMO and EU goals to cut GHG emissions requires major investments and technological changes that the industry has been slow to adopt. Without great efforts to shift to cleaner fuel sources and upgrading their vessels, the maritime sector could fall behind in meeting the global climate targets. This could not only lead to stricter regulations but also harm the industry's reputation, because customers and governments demand increasingly cleaner, more sustainable practices.

For smaller companies or those with older fleets, the combined impact of ETS and FEUM can be particularly challenging, as they do not have the resources to adopt these changes. If these companies do not adapt, they face financial penalties, potentially losing competitiveness as the sector demands cleaner, regulatory compliant operators. Overall, these EU and IMO initiatives represent a significant step forward for sustainability, but they can also result in a difficult and complex path for the maritime industry to cope with the regulatory, financial, and technical challenges to reduce emissions.

As stated, the unavailability of alternative fuels may even be the biggest barrier of becoming carbon-neutral. This has been stated by multiple experts, as also can be read in interviews with the commercial department of Jumbo Maritime B.5 and with DNV B.7. When the infrastructure and the availability of the fuel exists, this will be the breakthrough for the maritime industry to actually use it. It is first up to the "big boys" like Maersk to let the demand exist, since they have such a influence into the market and have fixed destinations in the world.

1.6 Research questions

As shown in the SWOT analysis, the maritime sector has numerous threats and opportunities in becoming more sustainable: the maritime sector appears to have similar challenges in becoming more sustainable and the availability of alternatives for the maritime sector continues to grow. Jumbo Maritime has specific strengths and weaknesses in making the transition to becoming future-proof with regard to reducing their GHG emission. To tackle the problem of how to reduce emissions, an analysis should be made. Each alternative has its own pros and cons which can become clear in a specific set of criteria, like the (operational) cost and the effect on regulatory compliance. Combined with the objectives of this thesis, coming from Jumbo Maritime, a complex issue emerges.
In summary, this thesis addresses the research gap in determining which technology to implement on an HLV by developing a structured approach to create a business case for reducing GHG emissions. The ultimate goal of this structure is to ensure that Jumbo Maritime remains future-proof. This business case evaluates various alternatives that can be integrated into the existing Jumbo Maritime vessels. The gap between the status quo and which alternative technology to implement, can be summed up by the main research question, stated next:

Which technological innovations are best suited for heavy-lift vessels in alignment with the objectives of Jumbo Maritime, the EU and the IMO for reducing greenhouse gas emissions?

This main question can best be answered with the help of multiple sub research questions, stated next:

1. *What is the current state of the IMO and EU regulations on reducing greenhouse gas emissions in 2024 and how are they related?*
   This is important because it defines the playing field in which this research operates. It shows how the maritime sector must comply with IMO and EU regulations for reducing GHG emissions. These regulations have changed over the years, so having an up-to-date overview is crucial to ensure that the framework developed is relevant and applicable today. Additionally, the regulations include phased milestones that companies must meet along the way. This means action cannot be postponed until 2050 so compliance requires continuous effort and improvement. Understanding these deadlines helps identify which measures need to be implemented now and which can be planned for the future.

By understanding both the current state of regulations and their future trajectory, this research can help identify the most effective strategies for Jumbo Maritime. It ensures that proposed measures align with existing compliance requirements while also preparing for upcoming regulatory shifts. This way, the company can remain competitive, avoid unnecessary costs, and work toward long-term sustainability in a structured and manageable way.

2. *What sustainable measures can heavy-lift vessels adopt to reduce GHG emissions in compliance with IMO and EU regulations while remaining economically viable?*
   As sustainability becomes more important, many new measures have been developed in the maritime sector to reduce GHG emissions. To find the best option for the HLV Fairmaster, an overview of available alternatives has to be created (long list) and analyzed, focusing on those most effective at reducing GHG emissions. But in this search, the measures can, for instance, not have a price that is too high due to the financially important mission of Jumbo Maritime: staying profitable in order to survive and stay future-proof. This is why classification criteria have to be generated which the measures need to pass in order to be potential solutions in reducing the GHG emission.

3. *What are the relevant criteria that influence the decision on whether a sustainable technology is a promising innovation which fits the financial mission of Jumbo Maritime and what is their relative importance?*
   Many alternatives exist, but not all are viable. The key question is: what criteria must an alternative meet to remain a potential solution? Some measures may be highly effective in reducing emissions, but if they require significant OPEX, they might not be financially feasible. Others may offer fuel-savings but come with drawbacks such as long installation times, impacting operations. Balancing these trade-offs is essential for making well-informed decisions.
   Jumbo Maritime's priorities play a crucial role in determining the best choice. This also defines what "best suited" means in the main research question: should financial feasibility and short payback periods be prioritized, or is long-term sustainability more important? Identifying these priorities is a core objective of this thesis. Through stakeholder input, key criteria such as ROI and installation time will be determined. By clarifying what Jumbo Maritime values most, this research will help guide decision-making and ensure that selected measures align with both strategic and operational goals.

4. *Which measures that decrease GHG emissions are the best choice in terms of robustness and viability for Jumbo Maritime's HLV Fairmaster?*
   The effectiveness of certain measures can vary depending on the situation. To ensure that the DSS provides reliable and practical recommendations, it must go through a thorough validation process. This includes a sensitivity analysis to test how changes in key factors (such as fuel-saving percentages, BWM weights, and initial inputs) affect the results. For example, if the weight of ROI is reduced, measures that rely on a high ROI score will become less favorable in the decision-making process. By analyzing different scenarios, the DSS can demonstrate whether its recommendations remain consistent and applicable in real-world settings. Validation further ensures that the recommendations align with industry expectations and practical feasibility.
   Additionally, verification tests are necessary to confirm that the DSS functions correctly, ensuring there are no errors in its calculations or logic. For example, if a scenario assumes no EU sailing time, the DSS should correctly indicate that there are no ETS or FEUM penalties. To achieve this, extreme values are used in the verification process to test how the system handles boundary conditions. This step ensures that the DSS produces accurate and reliable outputs under various circumstances.

2 Literature review

This chapter goes into literature that is analyzed in the scope of this thesis. First, it is described what sustainability entails and how this thesis fits in that topic. Next, there will be dived into the current state of the regulations which is the playing field in which Jumbo Maritime has to maneuver itself. Then, academic literature is analyzed which goes into challenges, opportunities and alternative technologies that result in decreasing the GHG emission of the maritime sector. This chapter is concluded with the identified research gap.

2.1 Definition of sustainability

Sustainability is a widely used concept nowadays. This results in the exact meaning of sustainability becoming more vaguely. Since this is a popular term and since this is also a core-topic in this thesis, it is important to describe what is exactly meant by it. This is what this section aims to do.

2.1.1 Three dimensions of sustainability

Although sustainability is widely used, it is commonly accepted that it has three dimensions, namely Social, Economic and Environmental, as can be seen in the Venn diagram in figure 4.
In a research by Kuhlman and Farrington (2010), the definition of sustainability has been studied and it is clear that it consists of three main parts: environmental, economic, and social sustainability. All three are important when discussing sustainability.

Environmental sustainability is the most obvious one, as many people think of it when they hear the word "sustainability." It focuses on keeping the planet healthy by reducing pollution and ensuring future generations can enjoy the same natural resources that we have today. This means limiting GHG emissions, reducing waste and protecting ecosystems from destruction. It also involves using resources wisely, since many, such as fossil fuels and clean water, are finite. If they are depleted too quickly, future generations may face serious shortages. Another key part of environmental sustainability is the transition to renewable energy and cleaner technologies. This includes changing from fossil fuels to wind, solar, and other sustainable energy sources to reduce GHG emissions. It also involves adopting practices like energy efficiency, circular economy principles and sustainable production methods that minimize environmental harm.

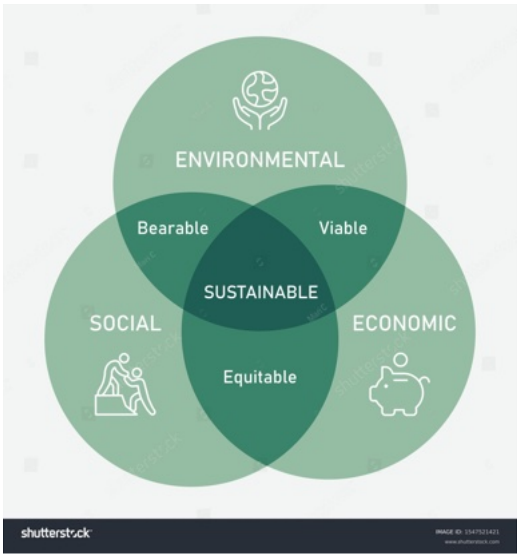

Figure 4: 3 dimensions of sustainability (Mari, 2019)

This is also what comes back into the economic dimension: without the economic importance, sustainability is not durable. The long-term profitability here is important because if resources now are depleted, the costs later are higher, which is not sustainable. If the "idea" goes bankrupt, there is also nothing to invest in. So, the conventional "profit" should be a bottom line of sustainability, just as being good to people by making the environment accessible for all, also to minorities and handicapped people (the social dimension). But we have to pay attention that the economic dimension is not all about money. It is thus about the long-term profitability, but also about the recourse efficiency, about the circularity. When there is invested in lean manufacturing by eliminating waste and re-using resources, the potential recourse depletion gets prevented.

Then the social dimension: happiness, well-being and welfare. Happiness can be seen as the ultimate goal of humans and having a healthy environment is a big predictor on whether that might be accomplished. But the social dimension is more: it is equity, how stuff is distributed across the society; it is the inclusion, which is usually operationalised as employment; and finally it is health, which can be expressed in life expectancy.

All three key elements must reach a level that everyone agrees on at the same time. When they are balanced, it becomes possible to create sustainable maritime transport and logistics that are both financially viable and safe for the environment and people (Hasanspahic et al., 2020).

As seen in figure 4, there is an overlap between environmental and economic. This is the stated financial viability where this thesis is scoped onto. Jumbo Maritime is a commercial company which means that they are aiming towards making profits in order to keep being future-proof. However, due to the GHG decreasing initiatives of the EU and IMO, they have to become more environmentally friendly. But the interaction between this financially goal of Jumbo Maritime and the necessity to decrease their emission, is a very complex problem. How can you stay economically healthy while having to invest in GHG decreasing measure?. That is where this thesis is about.

2.1.2 The relationship between sustainability and maritime industry

Research by Jonson et al. (2020) shows that compared to 2000, land-based vehicle emissions have generally decreased in western Europe due to regulations. However, this contrasts with emissions from shipping. Research states that emissions from the shipping sector have changed less than land-based emissions in Western Europe, and consequently, the contribution of ship emissions to air pollution in western parts of Europe has increased relatively (Gaisbauer et al., 2019). When cleaner marine fuels are used instead of conventional HFO, premature mortality and morbidity, related to ships, are reduced by 34% and 54%, respectively (Sofiev et al., 2018). In addition, as shown in the introduction of this thesis, maritime transport accounts for almost 3% of global GHG emissions, further highlighting the need for intervention. This shows the direct link between the maritime sector and climate change: shipping not only contributes to global warming, but is also affected by its consequences, such as rising sea levels, extreme weather conditions, and disrupted trade routes. These impacts create both regulatory and operational challenges that require the industry to take action.

Therefore, stronger international shipping policies are needed to achieve climate and health targets by jointly reducing GHG emissions and air pollution. It is clear that the shipping sector must reduce its emissions. To achieve this, various regulations have been introduced in recent years. The current state and the implications of the IMO and EU regulations, are described in section 2.3 and 2.4 respectively.
This leads to the next phase: how can the maritime sector reduce its emissions? This is where this thesis focuses on, specifically on technologies that improve energy efficiency while maintaining the same level of operational performance.

2.2 Regulations

Without additional policy action, the maritime shipping's GHG emissions are expected to increase as much as 16% from 2018 to 2030, and even 50% by 2050 (ICCT, 2022). To change this forecast, the IMO and the EU have separate approaches. These are the EU's Fit-for-55 (subsection 2.4), which refers to the EU's target of reducing net GHG emissions by at least 55% by 2030 compared to 1990, and the IMO's goals to be net-zero in 2050 (subsection 2.3).
Fit-for-55 entails the EU Emissions Trading System (ETS), FuelEU Maritime (FEUM), the Monitoring, Reporting and Verification (MRV) system, and the Corporate Sustainability Reporting Directive (CSRD). These are interconnected tools within the European Union's policies aimed at reducing CO2 emissions in the maritime sector. The IMO has the CII, SEEMP and EEXI/EEDI. In figure 5, a clear overview of the initiatives by the IMO and EU is given. Note, HLV are specifically excluded for the CII and EEXI regulations. However, since the CII will become applicable to them in the future, it is included in the figure. The CSRD is also not shown since this regulation is not for vessels but for companies and their sustainability initiatives, however, it is described in this thesis to be complete.

Organisation	EU	EU	EU	IMO	IMO
Measure	MRV	ETS	FuelEU	DCS	CII
Vessels	>5000GT cargo & passenger	>5000GT cargo & passenger	>5000GT cargo & passenger	>5000GT	>5000GT
	From 2025: GCV between 400 and 5000GT; offshore >5000GT	From 2027: offshore >5000GT			
Summary	Data collection tool, public benchmarks	EUA allowances to cover emissions	GHG intensity limit of energy used on board	Data collection of fuel consumption and benchmarking	Energy efficiency rating A-E based on DCS data
Emissions	Tank-to-wake (CO2, N20, CH4)	Tank-to-wake (CO2 but from 2026 also N20, CH4)	Well-to-Wake (CO2, N20, CH4)	Tank-to-Wake (CO2)	Tank-to-Wake (CO2)
Notes		Based on MRV data. GCV and offshore between 400-5000GT from 2027 to be announced	Has its own reporting requirements. Includes electricity received. Rewards for WASP.		Level A-E

Figure 5: Initiatives by the IMO and EU summarized (figure made by author)

2.3 Initiatives IMO: Net-zero 2050

In July 2023, the IMO agreed to revise its initial greenhouse gas (GHG) emissions reduction strategy. Initially in 2018, they stated a goal of reducing emissions from ships by just 50% in 2050 compared to 2008. The revised 2023 strategy sets a goal of being net-zero in GHG emissions from ships "by or around, i.e. close to, 2050". This is an enormous increase and this shows great ambition compared to the existing 2018 goal. Also, the IMO stated to reduce the GHG by at least 40% by 2030 compared to 2008 (IMO, 2023a), also see figure 6. Next, it is aimed at the uptake of zero and/or near zero emission GHG fuels, technologies, and energy sources: these must represent at least 5%, while striving for 10%, of the energy used by international shipping by 2030 (IMO, 2023b).

In 1997, a new annex was added to the International Convention for the Prevention of Pollution from Ships (MARPOL). This was the "Regulations for the prevention of air pollution from ships" (Annex VI) and its goal is to minimize the carbon intensity of global shipping and the amount of airborne emission from ships (IMO, 2010). This annex continuously evolved with more regulations (eg. EEDI and SEEMP) in order to reduce the negative impact of shipping on human health and the environment. To measure if ships comply with the ambitions of the IMO, in October 2016, mandatory requirements were added to the MARPOL Annex VI to record and report their fuel oil consumption. This is the IMO DCS and ultimately leads to the necessary data to make decisions on further measures to improve the energy efficiency of ships.

But while the IMO encourages port authorities and governments and other stakeholders to provide incentives for ships complying to their directives, there is currently no standardized enforcement mechanism for vessels with lower ratings. However, individual port states or regions may implement their own measures in the future, potentially restricting access to ports or imposing other penalties on consistently low-rated vessels (Nortech, 2023). This is already seen within IMO Member States, who are discussing proposals for the next set of GHG reduction measures of the IMO. These are similar to EU regulations, as can be read in paragraph 2.4. For starters, a maximum carbon-content for marine fuels has been discussed, even as economic measures, such as a GHG levy: emissions trading scheme (ETS) or some kind of incentive schemes for zero emission vessels (IMO, 2022). Therefore, ship operators should remain vigilant and proactive in improving their vessels' energy efficiency to mitigate potential risks associated with non-compliance.

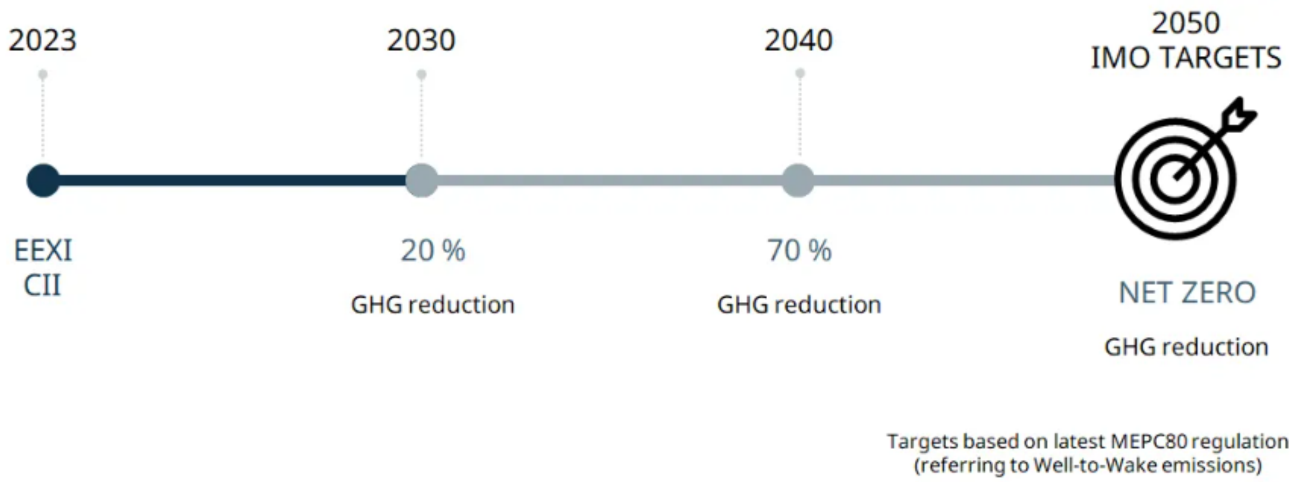

Figure 6: 2050 IMO targets (Wärtsilä, 2024)

2.3.1 IMO DCS

The IMO Data Collection System (IMO DCS) is a global regulation introduced under MARPOL Annex VI to monitor and reduce GHG emissions from international shipping. Since January 1, 2019, all ships of 5000 GT (which produce approximately 85% of the total CO2 emissions from international shipping) and above are required to track and report their fuel consumption annually. The collected data includes details on fuel type, distance traveled, and hours underway. Shipowners must submit this information to their flag state, which verifies the data and forwards it to the IMO.
In this system, shipowners must track key operational data, including fuel type, distance traveled, and hours underway. This information is submitted to the ship's flag state, which verifies the data before forwarding it to the IMO. By requiring ships to monitor and report their emissions, the IMO DCS encourages shipowners and operators to adopt more fuel-efficient technologies and operational strategies. The data collected can help identify areas for improvement and guide future regulations aimed at reducing the carbon footprint of the shipping industry. Since 2023, IMO DCS data is used to calculate ship's operational carbon intensity (CII) (IMO, 2024).
The IMO DCS is often compared to the EU MRV system, which also aims to track shipping emissions. However, there are key differences. While the EU MRV focuses on voyage-specific reporting for ships operating within the EU, the IMO DCS collects and analyzes data on a broader, aggregated level. This means that the IMO DCS provides an overall picture of global shipping emissions rather than detailed information on individual voyages.

2.3.2 CII and EEXI/EEDI

The CII is the Carbon Intensity Indicator and it is mandatory for all ships over 5000 GT per 1 January 2023, except when specifically excluded (like HLV). This is an index and it represents the amount of "grams of CO2 emitted per cargo-carrying capacity and nautical mile" (DNV, 2023a). This is a regulation which comes from the IMO and it assesses and regulates the carbon emissions of ships in relation to their cargo-carrying capacity and distance traveled. It forms part of the IMO's broader strategy to reduce GHG emissions from the maritime sector and its goal to be carbon-neutral by 2050. The CII states that ships must achieve specific annual reductions in carbon intensity, which aims at gradually reducing GHG over time. It compares the operational efficiency with 2019, which is the reference year.

The CII is calculated as the ratio of the ship's CO2 emissions per transport work, and it considers factors like fuel consumption, distance travelled, and cargo carried. The calculation is also depicted in the appendix A.1. Ships are then rated on a scale from A to E based on their carbon intensity, with A being the most efficient. Ships with lower ratings (D and E) are required to implement corrective action plans to improve their performance. The introduction of the CII pushes ship operators to adopt more sustainable technologies, improve fuel efficiency and explore alternative fuels to reduce their carbon footprint.

However, the heavy-lift sector does not agree completely with the CII directive. Since they do not control the idle time of their engines, they emit more than other maritime sectors. These idle times come forward due to needing power when laying in ports or at anchorage, the vessel needs to keep functioning. This is why heavy-lift companies like Intercargo propose the CII ratings to change. They found inconsistent efficiency indicators within the CII: "Vessels with E ratings often have lower average CO2 emissions compared to those rated A to D, suggesting the CII does not accurately reflect a vessel's true efficiency."(Kershaw, 2024).

In October 2024, definitions have been made by the IMO which entails which vessels need to adhere to their rules. It became evident that the heavy load fleet does NOT fall in the scope of the CII and the EEXI. This is shown in appendix A.9

EEDI stands for IMO's Energy Efficiency Design Index (EEDI) and this is approved in July 2011. It entered into force on January 1, 2013 and its goal is to reduce exhaust gas by improving energy efficiency on newly built vessels. It is mandatory for all designed vessels over 400 GT. The EEDI is the first global design standard aimed at combating climate change as caused by shipping. The standard will be made increasingly more stringent over time in order to comply to the IMO net-zero 2050 goals. The EEXI is not scoped onto the HLV, for now.

The Energy Efficiency Existing Ship Index (EEXI), is the same as EEDI but then applicable to existing ships. This targets their design efficiency and it thus requires ships to meet minimum energy efficiency performance standards, usually through technical improvements or retrofits.

So, in summary, the EEXI focuses on the technical design of the vessel to improve energy efficiency, often requiring physical modifications. In contrast, the CII focuses on the operational efficiency of how a ship is run on a day-to-day basis (e.g. speed, route optimisation), without going into technical changes to the vessel itself.

2.3.3 SEEMP

The SEEMP (Ship Energy Efficient Management Plan) was introduced in 2013 by IMO and it is enhanced in 2023, in alignment with the net-zero 2050 directive. It is an operational measure to improve the energy efficiency of operations of existing vessels and it is mandatory for all vessels over 400 GT from January 1, 2013. There are three parts of the SEEMP.

1. The first part is mandatory and must be kept live on board of all vessels over 400 GT and entails the ship management plan aimed at improving energy efficiency. This plan outlines operational measures which goal it is to improve the energy efficiency of a ship. Examples of this are optimizing voyage planning, the fuel consumption and the speed. This is all specifically for each and every ship and its operations.

2. The second part applies to ships over 5000 GT. The focus is of this part is on energy efficiency and these vessels have to collect and report data such as the annual fuel consumption, distance traveled and hours underway so that their fuel efficiency can be determined. This data will then be shared with the flag state of the vessel and they will then share it with the DCS for fuel oil consumption of vessels. When documenting this information, it becomes clear how important it is to have data quality control measures and a standardized data reporting format.

3. The third part is introduced to comply with the DCS for fuel consumption. Ships of 5000 GT and above must collect and report data on fuel consumption, distance traveled, and time spent at sea. The third part focuses on calculating the CII rating, using the data collected in part two.

The SEEMP is a tool that helps ship operators improve their energy efficiency, reduce fuel consumption, and ultimately lower GHG emissions. It is in line with the IMO's broader strategy to decarbonise the shipping industry.

2.4 Initiatives EU: Fit-for-55

The EU's Fit-for-55 consists of the MRV, ETS and FEUM for the maritime sector. These are described in the following subsections (European-Commission, 2024e). The Fit-for-55 is a step in the overall goal of becoming climate-neutral by 2050, which is stated in the European Climate Law (European-Union, 2021).

2.4.1 ETS

The European Emissions Trading System (ETS) requires installations and operators to pay for their GHG emissions. It was launched in 2005 on energy-intensive industry sectors and it was the first carbon market. The ETS is based on a "cap and trade" principle. This cap (or capacity) is reduced every year in line with the

EU's climate target. It has shown to work because by 2023 the emissions had been reduced by 47% compared to 2005, when it came into effect. The revenues that result from the sales of the ETS are used to finance the green transition and it covers the industrial manufacturing, the electricity and heat generation and the avaition sectors. These sectors combined result in 40% of the total GHG emissions in the EU (European-Commission, 2024g).

But in 2024, the ETS system got extended towards the maritime sector. Ship owners must buy and surrender emissions allowances on an exchange market to offset emissions reported under the EU Monitoring, Reporting and Verifying (MRV)-scheme. Emission allowances are purchased for the fleet as a whole, not per individual ship. MRV reporting remains at the ship level. The ETS is the EU's main carbon pricing mechanism. The goal of the ETS is to reduce emissions through market incentives. Until recently, the maritime sector was largely excluded from the ETS. However, with the inclusion of shipping, vessel operators now have to pay for their CO2 emissions, creating a financial incentive to reduce emissions. In figure 7, the planning is seen of the upcoming years per ship type.

So, started in 2024, shipping companies operating cargo and passenger vessels over 5000 GT need to comply with the EU ETS regulations. This means that these companies must account for their GHG emissions by holding emission allowances (the ETS), which they have to purchase, corresponding to the amount of CO2 they emit. The cap-and-trade structure of the ETS creates a financial incentive to reduce emissions and companies that reduce their emissions enough to be below their amount of allowances, can sell the excess of those certificates to others. Other who are exceeding their cap must buy additional allowances.

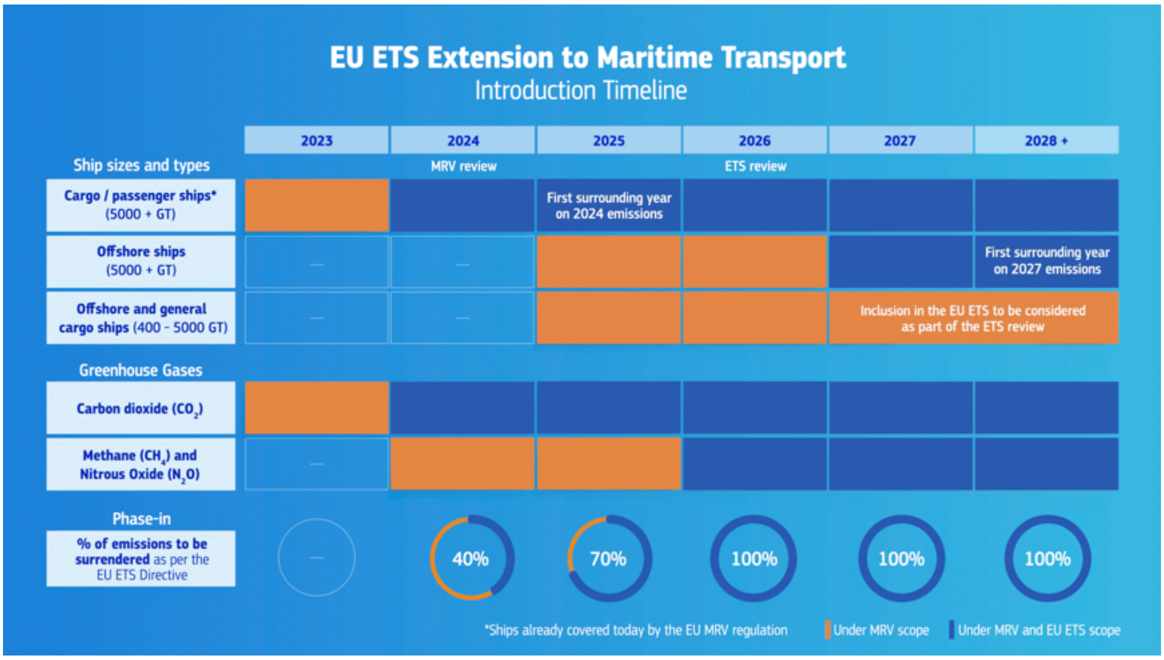

Figure 7: ETS planning (European-Commission, 2024c)

But as seen in the figure, from 2025, offshore ships over 5000 GT also have to answer to the regulation. From 400 GT, offshore and general cargo vessels also have to account their CO2 emissions. But that is not all: next to CO2, also CH4 and N20 are brought into the equation. But it is implemented with different phases. In 2024, 40% of the emission has to be paid; in 2025, 70% of the emission but in 2026, all the emissions have to be accounted for by the emission certificates. Lastly, from 2025, by 31 March of each year, shipping companies must submit an emissions report at the company level. These aggregated emissions data at the company level has to include: "all ships under its responsibility; and the sums of all ships' total aggregated emissions of greenhouse gases, expressed in tonnes of CO2 equivalent, and disaggregated by individual greenhouse gas", as stated by the European Maritime Safety Agency (EMSA, 2024).

2.4.2 FEUM

The FEUM (FuelEU Maritime) regulation is only applicable to the maritime sector and gets into effect in 2025. It is a part of the Fit-for-55 package and thus promotes the use of renewable, low-carbon fuels and clean energy technologies for ships in order to support decarbonisation in the sector. It sets limits for the GHG emissions for all ships over 5000 GT arriving at European ports. The targets entail 2% decrease by 2025, 6% by 2030 and ultimately 80% by 2050 (European-Parliament, 2023), the entire planning is seen in table 2.

Year	Percentage reduction (%)
2025	2
2030	6
2035	14.5
2040	31
2045	61
2050	80

Table 2: GHG intensity limit compared to reference year 2020

There is a time schedule which shipowners have to adhere to. Each year, by 31 January, shipowners must submit emissions data to the verifier. Then, by 31 March, they will receive a report from that verifier and any applicable penalties need to be payed. Then finally, the annual FEUM certificate is received at the end of June. The emission data which needs to be submitted, exists of the type and volume of energy that is consumed, while docked and at sea, incorporating well-to-wake emission factors for all fuel types. FEUM applies to 100% of the energy used on voyages (and port calls) within the EEA, and for 50% of energy used on voyages entering or exiting the EEA. But since companies prefer to pay less, they might use evasive tricks. So, the FEUM incorporated a rule that states that a stop in transhipment ports located outside the EEA but which is "less than 300 nautical miles from an EEA port, need to include 50% of the energy for the voyage to that port as well, rather than only the short leg from the transhipment port." (DNV, 2023c). Well-to-wake means the emissions from the beginning of the production of the fuel, to the use of the fuel. This is clearly depicted in figure 8.

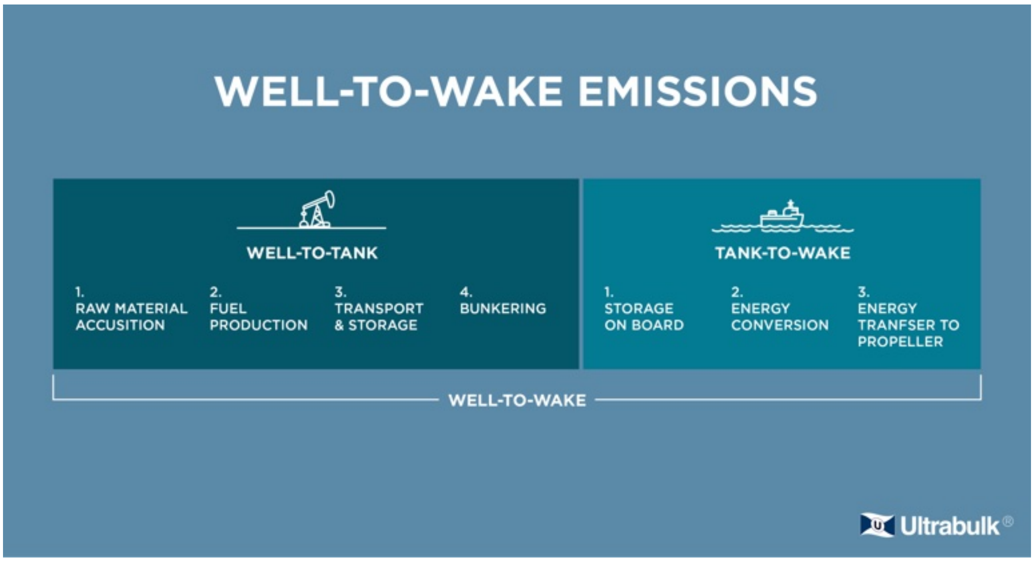

Figure 8: Well-to-wake (Jonsson, 2024)

The FEUM sets targets for reducing the yearly average GHG intensity of the energy used by a ship, or by a fleet of ships and then reduces these emissions on an annual basis according to a linear reduction factor. It is designed to mandate the use of cleaner fuels in ships to reduce greenhouse gas emissions in the maritime industry. This works closely with the ETS because using lower-carbon fuels reduces CO2 emissions, which in turn lowers the cost of emission allowances under the ETS. FEUM sets specific technical and fuel-related requirements.
The FEUM has a compliance penalty, as stated in the FEUM Regulation: "Without prejudice to the possibility of complying through the flexibility and pooling provisions, ships that do not meet the limits on the yearly average GHG intensity of the energy used on board should be subject to a penalty that has dissuasive effect, is proportionate to the extent of the non-compliance and removes any economic advantage of non-compliance, thus preserving a level playing field in the sector (the 'FEUM penalty'). The FEUM penalty

should be based on the amount and cost of renewable and low-carbon fuels that the ships should have used to meet the requirements of this Regulation." (Schroer, 2024).
The reported emissions are per ship and not aggregated across the whole fleet. This results in the possibility to see the efficiency per ship and its impact on the total emission. However, emissions can be **pooled** between two or more ships which are verified by the same entity to achieve compliance per individual ship. An example: if one ship has 120% compliance and another has 80%, the balance is 100% compliance. Note, ships do not necessarily have to be controlled by the same company (Bureau-Veritas, 2023). Thus, pooling lets shipowners to combine the GHG intensity of different vessels in their fleet. This potential means shipowners don't have to make sure that every single vessel meets the emissions targets individually, as long as the fleet average aligns with the requirements. Pooling thereby encourages investment in low-emission vessels and helps balance out a fleet's overall emissions performance, making it easier to meet the FEUM targets. What shipping companies also can do to reduce their CO-footprint, is to buy fuel together with other companies, called joint fuel sourcing. Due to this, companies can get better prices and a more stable fuel supply, which can help make low-carbon fuels like biofuels, which are more expensive, more accessible.

Reward (factor) FEUM

- OPS = Onshore Power Supply
  The vessel gets a rewarded by using OPS from 2025 to 2030. If they use it, the energy will be zero-rated, which means that it does not count towards the annual GHG intensity of the ship. From January 1 2030 though, container and passenger ships must connect using OPS (or a zero-emission alternative) at TEN-T core maritime ports. These are the Trans-European Transport Network maritime ports that are strategically important in the European Union. This helps reduce the GHG emissions because onshore power will be used (which can be generated using green sources like wind turbines) instead of running auxiliary engines, which consume fuel and emit emissions. Note, short stays of less than two hours moored at the quayside are excluded, just as when a zero-emission technology is used (European-Commission, 2024d). If shore power is used, it could account for up to 7% of total energy consumption while vessels are in port (DNV, 2024a).

- WASP
  When using WASP (kites, rotors, sails), this helps with complying to FEUM due to a reduction of the calculated annual GHG intensity of the energy used onboard. This supports economic feasibility for WASP and results in a reduction in the need to invest in more expensive renewable and low-carbon fuels. The reward can go up to 5%, it depends on the ratio between the effective wind power (Pwind) and the installed propulsion power of the ship (Pprop). This is also depicted in appendix A.8.

- RFNBO = Renewable Fuels of Non-Biological Origin
  The GHG intensity of RFNBOs will be halved when calculating the actual GHG intensity of the energy used on board ships. If the share of the use of RFNBO is less than 1% of all fuel usage within the scope of the regulation between 1 January 2025 and 31 December 2031, then a sub-target is mandated which entails the use of 2% RFNBO from 1 January 2034 (Lloyd's-Register, 2024). This motivates to use RFNBO since these are typically created using renewable electricity, which significantly reduces the Well-to-wake principle.

Concluding, FEUM focuses on the type and quality of fuel used by ships in EU waters, setting specific GHG intensity limits each year to encourage cleaner fuel use. These cleaner alternative fuels, like biofuel, must meet strict GHG reduction thresholds. This makes sure that not only the use of the fuel is environmentally friendly, but also its entire supply chain, from production to end-use, is sustainable, as seen in the well-to-wake principle. Companies can use pooling with multiple ships to comply to the regulation, as well as joint fuel sourcing.

2.4.3 MRV

MRV (Monitoring, Reporting and Verification) is crucial for both the ETS and FEUM as it provides the accurate measurement of GHG emissions from ships. The system gives the baseline data needed to calculate: how much CO2 must be reported and paid for under the ETS; and to verify whether the fuels used, meet the requirements of FEUM. Also, MRV requires that each company has a monitoring plan which contains key information such as fuel use, GHG emissions, travel distance, and cargo amount. This data must be recorded accurately and consistently, following EU guidelines. The plan is essential to the MRV system because it specifies exactly how (methods and processes) each company will track key information on emissions. Also,

the plan itself has to be prepared according to the EU guidelines as stated in the European-Commission (2024f), which makes sure that the data collection is consistent and accurate across all companies.
Once this information is collected, it goes into a yearly report. Companies must then submit their monitoring plans for approval and any changes to the plan must be documented and resubmitted. A third-party, the verifier, checks to make sure it is complete and accurate. Companies must submit these verified reports by specific dates each year so that the EC can build a transparent, publicly available database of emissions from the maritime industry. This step is crucial for making a reliable system for tracking data on the emissions that can be consistently verified and used for further regulatory compliance, like the EU ETS. Without the MRV system, there would be no reliable way to measure ship emissions, which is key for compliance with both ETS and FEUM by giving a reliable record of emissions data. So, the MRV makes rules about the reporting of emissions and other relevant information from ships calling at EEA ports (DNV, 2024b).
In this reporting, CO_2 emissions are the largest component of GHG from maritime transport, but CH_4 and N_2O emissions are also important contributors. Thus, as part of the 'Fit for 55' package, MRV was extended to those other emissions in 2024, this is also the reason why the term "CO2" in the regulation, was changed to "GHG". In 2015 the MRV was implemented, the first reporting period was in 2018 and in 2023 it was updated due to the European Green Deal. And, from 1 January 2025, it will also apply to general cargo ships between 400 and 5000 GT and offshore ships of 400 GT and above (European-Commission, 2024b). The whole timeline is shown in figure 9.

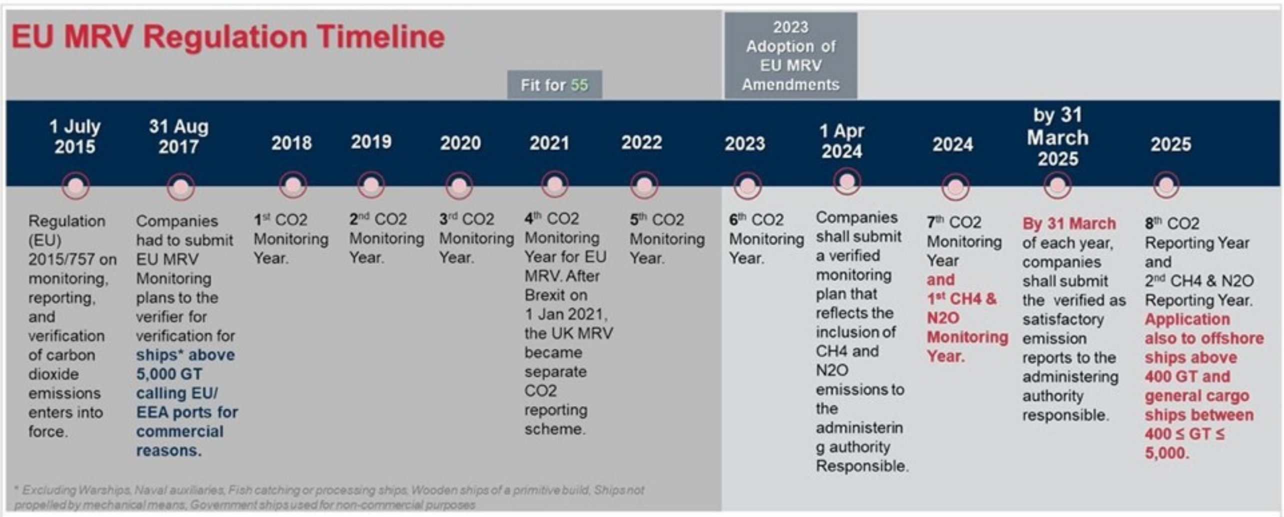

Figure 9: Timeline MRV (ABS, 2023)

2.4.4 CSRD

On 5 January 2023, the Corporate Sustainability Reporting Directive (CSRD) has entered into force. It goes into modernizing and strengthening the rules that go into the social and environmental information that companies have to report. The first companies have to apply to the new rules for the first time in the financial year of 2024, for reports published in 2025. These companies, which are subject to the CSRD, have to report according to the ESRS, which provides a framework for companies to report on ESG topics (Environmental, Social, Governance) (European-Commission, 2024a). The CSRD will cover all large companies that meet two of the following three criteria (PwC, 2024):

- Turnover exceeding €50 million per year;
- A balance sheet total of more than €25 million;
- More than 250 employees (averaged over a year).

It emphasizes "forward-looking information to assess companies' long-term sustainability strategies." (ClimatePartner, 2024) and are depicted in appendix A.6. In this figure, the general principles for all sectors are described in the ESRS 1. In ESRS 2, the sector specific rules are stated as also depicted in the figure, divided in ESG. This is something the Sustainability Manager is working on.

2.5 Research into alternative technologies

Since the need exists for decarbonisation of vessels, a lot of research has been done in this field. One of these, research by Bouman et al. (2017), has reviewed around 150 studies to provide a comprehensive overview of potential technologies. It went into different GHG reduction measures which are implemented in the shipping sector, since CO2 emissions from maritime transport represents around 3% of total annual GHG emissions. In this research, a large variability in CO2 reduction potential was found between the reported measures. However, CO2 emissions can be reduced by a factor 4 to 6 per freight unit transported and the emissions can be reduced by more than 75% based on the current technologies. The article has divided the measures into six groups: hull design; economy of scale; power and propulsion (including energy saving devices); speed; fuels and alternative energy sources; weather routing and scheduling. Not all of these are relevant for this thesis since they fall out of the scope. This is the economies of scale, which increases the load per voyage. It can also be seen that when cargo-carrying capacity is doubled, the required power and fuel consumption increases by about two-thirds. This makes that fuel consumption per freight unit is reduced. This is also out of the scope since Jumbo Maritime takes jobs and already tries to maximize their load when sailing. It is very different from container vessels since heavy-lift shipping is always different (in dimensions).
The rest of the groups of measures have relevant information. Starting with the hull design. The actual design of the hull falls out of the scope, because this is applicable to new ships and not existing ones (HLV Fairmaster). But technologies like Air Lubrication System (ALS) show to decrease CO2 emission by 1-15% (Tillig et al., 2015). This is a technique which reduces the frictional resistance between the ship's hull and the water by using a sheet of air (bubbles). Also, hull coating appears to be an interesting alternative that decarbonizes by 1 to 10% (Faber et al., 2011). Then recovery of the waste heat with 1 to 20% (Lindstad et al., 2015). Wind power with a kite or sails shows a decrease in GHG by 1 to 50% (Psaraftis, 2016). And speed optimization reduces 1 to 60% (Lindstad et al., 2016). These measures are also depicted in A.2. The problem, however, with this analysis is that it is not applicable onto special cargo vessels or specifically HLV. These are significantly different from them due to the diverse field of jobs and dimensions of those jobs. The results of the article remain very generic because of the diversity of the studies that go into different kinds of vessels. However, it is very useful to see that different technologies are being researched and it being a hot topic. There are a lot of implementations possible; for example, next to a sail, a kite is also possible. The ships onto which the different alternatives are implemented are different in each research. But there is not yet been done any research of different technologies which result in decarbonisation on HLV.

2.6 Opportunities and challenges for the maritime sector

2.6.1 Opportunities

Initiatives to reduce CO2 emissions can also be found in different fields, next to hardware, also software and other technological advancements. In the research by Oloruntobi et al. (2023), it studies the impact of the technological revolution on the maritime industry. Big changes are happening in the world: growth of the population, the rise of climate warming, and the interaction between these two. Climate change is expected to further worsen the decline in food and water supplies, which in turn drives the demand for water-based trade worldwide. This consequently leads to congestion in the ports of mega-cities, while emission needs to be reduced. This is where technology comes into play. Over the last 15 years an enormous effect of digitalization is seen, like AIS (Automated Identification System) and SOLAS (the International Convention for the Safety of Life at Sea) with its implications like the EPRIB (Emergency Position-Indicating Radio Beacon). This has improved sea safety by using the current technological possibilities in regulation. Currently, this effect can be seen again. New technological advances like the Internet of Things and AI can and should be used. Especially with the regulations of the IMO and the EU on the decarbonisation of the seas by becoming net-zero. Now, there are already initiatives like ICT-linked ships, autonomous ships, remote ship operations. Smart ships and smart ports can reduce seagoing vessel traffic, congestion, waiting times, and shipping costs. This shows that digitalization and technological advances can improve existing processes in maritime transport. This enables shipping companies, in turn, to optimize their operations, boost the productivity, efficiency and finally sustainability.

2.6.2 Challenges

Like any other industry, the maritime industry needs to adapt to the needs of the modern world and take care of the environment. Hasanspahic et al. (2020) have studied the sustainability and environmental challenges of the modern shipping industry. They state that "one of the main challenges of maritime transport is to implement innovative solutions to protect the marine environment. However, it is quite challenging to achieve both ecological and economic benefits at the same time. That is why it is very important to apply the win-win principle, which refers to the sustainable development of maritime transport." To do this, they have made an overview of relevant and emerging technological (logistical) solutions aimed at reducing shipping GHG emissions. Compared to other modes of transport, maritime transport has the lowest carbon-footprint per tonne-kilometer due to their enormous mass of cargo. But since the expectation is that it will grow continuously if nothing is done, measures need to be taken to reduce their emission. They state that this can be done with:

- Changes in hull design;
- Changes in power and propulsion systems;
- Alternative fuels;
- Alternative energy sources;
- Exhaust gas abatement technologies, like CCS (see section 3.5.2).

The article states that the main challenges for decarbonizing the maritime industry lie in the balance between the three (described) dimensions of sustainability: economical, social, environmental. These three have to be in balance in order to work, by being financially viable and not destructive to the environment and humans. But finding this balance is much harder, since the direct initial consequences of sustainable initiatives may not be economically beneficial. Making changes on the vessels logically costs money, but in the longer run they might become beneficial. It is the measure that is chosen and on which it depends. Some measures might show a big decrease in fuel and emission, by, for example, using sails. But when the wind is not blowing in the right direction, it may look like a bad investment. However, there are other consequences that may result from a measure, like emission discounts on the FEUM. As can be seen, it is difficult to determine which implementation satisfies all three dimensions, and this is precisely the challenge.

The research by Koilo (2019) also looks at the sustainability issues of maritime transport and the main challenges of the shipping industry. She found that the challenges for sustainability lie in the balance of the three dimensions of sustainability (again). But specifically for decarbonisation, she found that the challenges lie mainly in:

- High costs of transitioning to alternative fuels such as hydrogen and ammonia. And the availability of these fuels in the future;
- Operational efficiency improvements to reduce emissions while maintaining profitability is difficult for the shipping industry;
- Uncertainty about technological advancements.

The article covers three different types of ships in Norway, which are: deep-sea fleet; short sea ships; and offshore vessels. HLV, however, can fit into both the offshore and deep-sea fleet categories, depending on their use. When used for installing heavy and oversized cargo, such as oil platforms or wind turbines, to offshore locations, they are considered part of the offshore vessel fleet. However, when these vessels carry large equipment across the oceans for industrial projects, they belong to the deep-sea fleet. Their classification largely depends on the specific mission and operational environment.

Lee et al. (2019) has also studied the sustainability challenges in maritime transport and logistics industry. They stated that getting more sustainable, and then specifically decarbonisation, comes with the following challenges:

- Alternative fuels such as LNG, hydrogen and biofuels;
- High costs of retrofitting vessels with clean measure;
- High operational for sustainable technologies;
- Complying with increasingly stringent international regulations;
- Maintaining economic viability while transitioning to greener practices.

As can be seen, being economically beneficial is a big part of the challenge. But what has also been a great topic in their article, is the social factor. This is due to accidents with the handling of (heavy) equipment and exposure to harmful substances, such as fuel emissions. The latter is then also an issue in terms of sustainability. Ships emit very heavy emissions at sea and breathing them in can actually result in earlier deaths. They are also sailing past coasts, and the impacts of shipping operations on coastal communities have been shown to be significant. This is again the social dimension of sustainability.

2.7 Conclusion - Research gap

In this chapter, it has become evident that multiple initiatives exist on decreasing GHG emissions by the IMO and the EU. The regulations of the EU are the MRV, ETS, FEUM and CSRD. These are relevant for the heavy-lift sector in European waters and thus for Jumbo Maritime. Of the IMO, initiatives are the CII, SEEMP and EEDI/EEXI. The heavy load carriers fall out of the scope of the CII and EEXI, as seen in appendix A.9. However, HLV do need to have a SEEMP.

There is no academic literature existing on the decarbonisation of any kind on HLV, which is a direct reason why this thesis is relevant. This is found by using the following search term in Google Scholar:
"heavy-lift vessel" AND "sustainability" OR "decarbonisation" OR "carbon footprint" OR "innovation"
This can be explained by the fact that heavy-lift is a relatively small sector within shipping, that within the sector not many comparable ships exists with such specific characteristics and irregular operational profile. Most studies focus on large coherent groups of vessels with regular destinations since these are the most occurring which means their study is more relevant. This shows the gap and thus the need for this thesis and a DSS.

Academic literature shows that many alternative technologies have been implemented on ocean-going vessels to reduce GHG emissions. Studies on different vessel types confirm their specific effectiveness. However, the challenge remains in identifying the best measures for HLV. They differ from regular ocean-going vessels due to their changing cargo dimensions, large cranes on deck, and unique operational demands. For example, the installation of sails could affect the positioning and use of the cranes, which negatively influences the operational flexibility. Depending on their specific job, HLV can fall into both offshore and ocean-going fleet categories. When installing objects on offshore locations, they are considered offshore and when they are transporting objects towards a destination, they are ocean going. However, categorizing them within a standard ocean-going fleet does not fully capture their constraints, as they carry oversized loads that impact vessel design and operations.
A key feature of HLVs is their high lifting capacity, distinguishing them from standard construction vessels (which typically lift less than 250 tons). The Fairmaster, the vessel studied in this thesis, has a lifting capacity of 2×1500 tons $= 3000$ tons, making it significantly different from typical cargo carriers.

This highlights a major gap: there is still no clear approach to reducing GHG emissions on HLVs. Their unique design and operational constraints require tailored solutions that go beyond conventional emission reduction strategies for ocean-going vessels.

What also has come back numerous times, is the similarity between the challenges called by the maritime industry. Alternative fuel has been called as a solution but has shown to be a challenge due to their low technological readiness level (TRL), high cost, or both. But what is relevant for this thesis, WASP, hull, heat recovery and propeller design have been shown to be recurring topics of interest. Also, the costs have been stated to be a huge factor in the challenge of being more sustainable by decarbonising. The fact is that it costs a lot of money to retrofit the ships to a more operational efficient vessel. This economic viability is next to a challenge, also a prime goal for the maritime companies, because without profit, they will go bankrupt. How to mitigate these challenges and how to overcome them, with which measure, and then specifically for the HLV, is still unknown.

Lastly, it has become clear from the studies that the maritime sector have an almost universal challenges and solutions for the problem of reducing their emissions. All of them know that their emissions need to be reduced, whether it is due to regulatory compliance, client attractability or vision of the future. So, the question remains, what is specifically important in the decision for choosing a specific measure when wanting to reduce their GHG emission?

3 Alternative measures that decrease GHG emission

Different measures can be a viable alternative to make vessels reduce their GHG emission. These technologies can range from purely hardware to purely software. This thesis solely focuses on measures that reduce the GHG emission of HLV when taking their financial concerns at hand since it remains a commercial business: new building and extensive retrofitting are out of scope. Eight alternatives are analyzed and used in this thesis. These come from a long list of the IMO (2020), Bouman et al. (2017) and Jumbo Maritime, which has been shortened with regard to the scope, also see appendix A.10. In this section, these alternatives are described. In figure 10, an overview is seen which shows the alternatives; the chosen manufacturer; and the category on which it has an effect, considering the decrease in GHG emission. The manufacturer was selected on the basis of their strong reputation and Jumbo Maritime's established positive relationship with them. It is needed to have a manufacturer with each alternative since every alternative needs input data for the costs, fuel-savings amount, etc.

	Manufacturer	Energy efficiency	Renewable power	Hull optimisation	Energy-saving	Decarbonisation
WASP	Bound4Blue		X		X	X
Wavefoil	Wavefoil		X		X	X
ALS	Alfa Laval			X	X	
Hull Cleaner	Damen			X	X	
Flipper zipper	Jumbo Maritime			X	X	
PBCF	Wärtsilä	X			X	
Eco-control	Wärtsilä	X			X	
Heat recovery	Orcan	X			X	
VLSFO						
MGO		X				
Biofuel						X

Figure 10: Alternatives (figure made by author)

3.1 Renewable power

Waves and wind are two systems that can be used for free renewable energy. This already happens in wind farms and hydroelectric power plants. Since promising innovations have been made in this field with respect to the maritime sector, they are described in this section. These are the WASP and the Wavefoils. Both of these systems use pressure to generate forward kinetic energy. This process works by using foils in, respectively, wind and water environments, which saves fuel.

3.1.1 Wind-Assisted Ship Propulsion (WASP)

Sailing has been used for thousands of years because it relies on the wind, a natural and free resource. Long before engines were invented, people used sails to travel across the seas and oceans, explore new lands, and trade with others. Next to that, sailing has been proven to be a reliable and cost-effective way to travel long distances without needing fuel. Over time, sails and navigation methods improved, making sailing even more useful. But when the engines were invented, they became more redundant due to the effect of not having to rely on the wind and the wind direction. But now, as a result of climate warming, sources are again sought that do not need any fuel to cut emissions. In addition, the wind is also free, which makes it a financially attractive option again.

Currently, there are 48 large ocean-going vessels that use WASP, with more than 80 rigs that result in three million DWT of shipping. Furthermore, "there are nine wind-ready vessels and 24 more pending installations and primary wind newbuilds underway along with a further 20+ smaller sail cargo and small cruise vessels using wind. Together, that is more than all the large ships currently operating using new low- and zero-emissions fuels combined." (IWSA, 2024). Propulsion with the help of wind power is also a technique that has been making a comeback in shipping. Research by Khan et al. (2021) has reviewed different types of WASP and its latest developments. They also showed that WASP has the greatest potential to reduce GHG. This is seen in appendix A.2. Three types of WASP are described in the article, but since the scope is on heavy vessels, one version of these is used in this thesis, which is using suction wings. The other ones, using soft- or rigid sails and the kite, have been shown to be inefficient on heavy ships due to space-usage (compromising free-deck space, crucial for heavy-lift operations due to limiting area available for paid cargo) and limited effectiveness respectively.

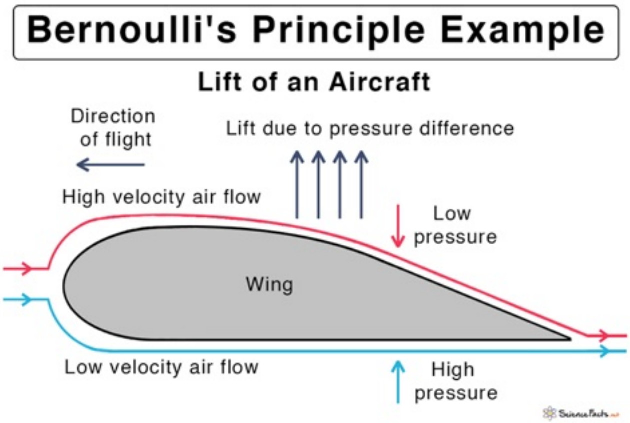

Figure 11: Bernoulli effect (Wilk, 2024)

Ventifoils, currently installed on HLV Jubilee of Jumbo Maritime (in 2024)
The suction wind foils, such as the Ventifoils by Econowind, have been already been fitted aboard one of the ships of Jumbo Maritime. It is a wing-shaped element which is equipped with vents and an internal fan that utilises so-called boundary layer suction in order to to improve operational efficiency in terms of propulsion. Its advanced aerodynamic design allows it to generate significant thrust for ships despite its compact size. By using "smart suction" technology, it doubles its propelling force (VB-North-Sea-Region, 2023). They work in a similar way of airplane wings: using a specific form which creates a low pressure zone on the side with the fast-moving air. This is also known as the Bernoulli Effect, also visually depicted in 11. At the TU Delft, a Master's thesis was written on this specific topic by Borren (2022). He investigated the interaction between two Ventifoils on deck of a ship, considering distance and wind direction. The outcome was that the most negative interaction came to exist if the foils were in parallel to the wind direction and close to each other. This aerodynamic interaction can reduce the lift and drag coefficients by multiple tens of percentages relative to a single isolated Ventifoil. The expected fuel-savings due to the Ventifoils are 2-4% according to Jumbo Maritime.
In case of big winds or other circumstances, it can reef (reduction in size) when necessary. One of the key advantages of installing larger Ventifoils on a vessel is the increased thrust, which directly translates into greater fuel-savings. Econowind (the manufacturer of Ventifoils) states that ships can sail the same distance and while reducing their fuel consumption up to 30% (Econowind, 2024). Lastly, they can fold and rotate around their axis, which ensures that access to the ship's cargo hold is maintained at all times, which is a must for HLV. However, these wind foils come with a hefty price tag.

Figure 12: An illustration of Bound4Blue eSails on the Maersk tankers (Camps, 2024)

Chosen alternative for this thesis: Bound4Blue
Bound4Blue is another company that offers mechanical sails. These sails are, just as the Ventofoils of Econowind, suction sails. These show to offer significant power savings and have been installed on numerous vessels. On five tankers of Maersk these will be installed in 2025/2026 and "The systems are expected to deliver double-digit percentage reductions in fuel consumption and CO2 emissions per vessel" and "The autonomous eSAILs work by dragging air across an aerodynamic surface to generate lift and propulsive efficiency, reducing fuel consumption, OPEX and emissions." (Buitendijk, 2024a). They offer two sizes: 18,5 and 22 meters. The higher the sail, the more advantage can be achieved since winds are more powerful at a higher altitude. In a design, Bound4Blue showed that they can mount two of those suction wings on the deck house, figure 13. This offers a great advantage compared to where the Ventifoils were installed, which was between the two cranes. Between two cranes results in a loss of free deck space, and free deck space is crucial in heavy-lift operations. The more free deck space, the larger the variety of objects that can be transported. The other advantage has actually already been described: installing them on the deckhouse means that they are higher in the air, which results in more power that they can use.
This is the type of WASP that is used in the decision support system.

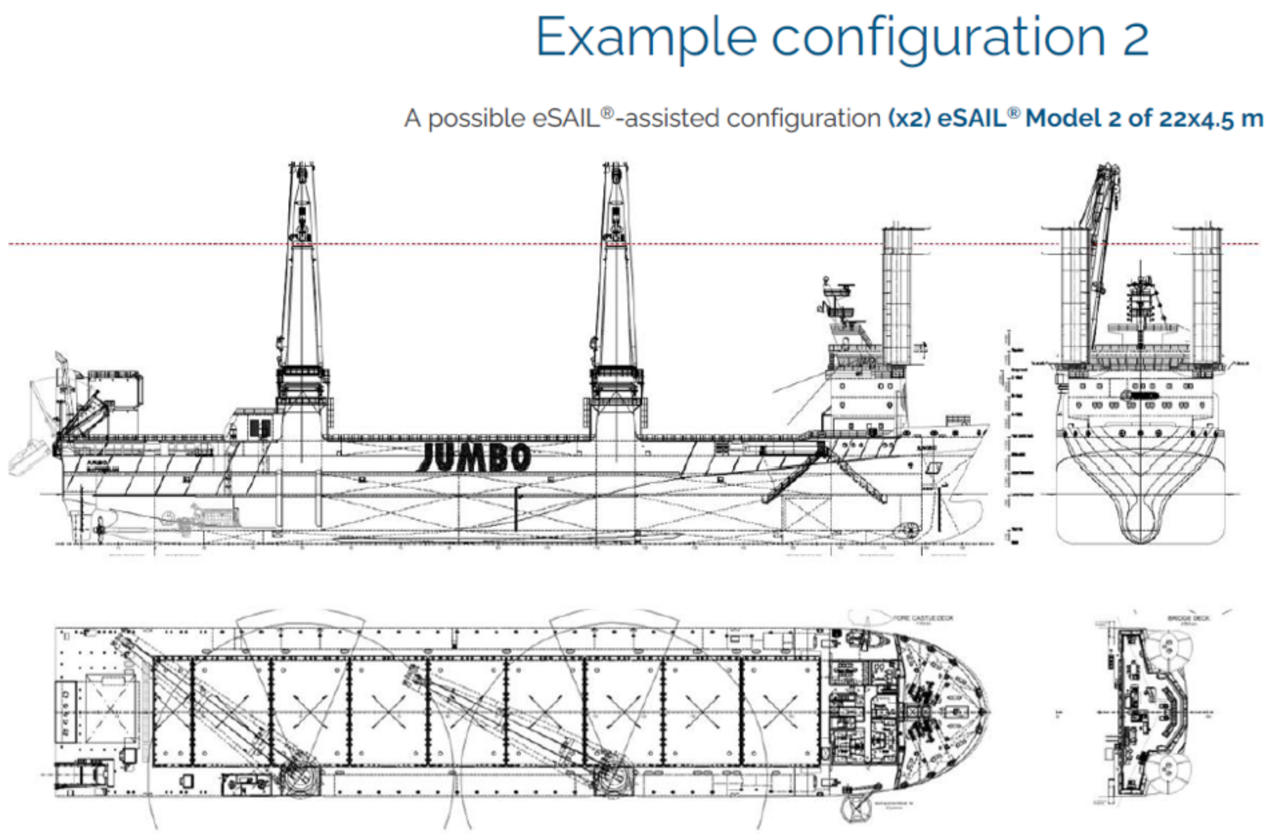

Figure 13: Configuration of the HLV Fairmaster with the Bound4Blue sails installed on the deckhouse (Copyright Bound 4 Blue, 2024)

3.1.2 Wavefoils

Next to a WASP, which is a windfoil, there is also a new concept called a wavefoil. It is an innovative technology which is designed by Wavefoil to improve the energy efficiency of ships by using the natural energy from ocean waves. It is depicted in figure 14. Savings go from 5-15% and they have been installed on numerous ships (Wavefoil, 2024). It uses retractable foils which are installed on the bow of a vessel, which move due to the up-and-down motion of waves. As the foils move, they generate additional thrust and this does effectively propel the ship forward without requiring extra fuel. The foils generate lift, like an airplane wing, when the vessel is moving up and down in waves. The lift has a forward thrust component which is larger than the drag, making it an effective system (Zhang et al., 2022). The technology is also especially beneficial in regions where there is consistent wave activity, by allowing vessels to convert this otherwise not used, renewable energy source into practical forward motion.

Figure 14: Wavefoil (Wavefoil, 2024)

A key feature of the Wavefoil system is that the foils are retractable. This means they can be extracted from the hull when the ship comes into conditions with waves where the foils can be very effective. They can also be retracted when they are not needed, such as in calm seas or when the ship is entering port or docking. This is a big advantage because the extracted Wavefoil does result in extra resistance in calm seas (Steen and Bøckmann, 2018) and there is of course the risk of colliding with submerged objects. This flexibility allows the ship to maximize the benefits of the system without compromising maneuverability or even safety in situations where wave propulsion is not needed.

By giving the vessel extra forward motion, it reduces the ship's fuel usage. This makes that the Wavefoil contributes to lower operational costs (Steen and Bøckmann, 2015). In addition, it is valuable for shipping companies that want to reduce their GHG emissions and comply with the environmental regulations of the EU and the IMO, which have become increasingly strict in the maritime industry. Thus, by integrating Wavefoil technology, ships not only become more economically efficient but also play a role in mitigating the environmental impact of global shipping, which is a significant contributor to GHG.

3.2 Hull optimization

When looking into ways on how to reduce the GHG emission on vessels, there can be looked at the hull of the ship. There are different options which can be implemented on vessels, these are: the Air Lubrication System (ALS); cleaning the hull to prevent drag by fouling building up; and the Flipper Zipper. These alternatives are described in this subsection.

3.2.1 Air Lubrication System

The Air Lubrication System (ALS) is a promising technology that is used on vessels in order to reduce drag and thereby improve fuel efficiency. It has first been implemented by the US Navy in order to conceal engine room noise, however, later scientists and scholars became interested in its potential to reduce drag resistance on the hull (ABS, 2019). It works by creating a layer of airbubbles between the ship's hull and the water. This is achieved by pumping air beneath the vessel from the front, which forms a blanket of bubbles that reduces the friction between the hull and the surrounding water, which otherwise exists when a smooth hull is used. This frictional resistance is one of major resistance components, approximately 60-70% of the total resistance (Jang et al., 2014). The impact of not using a smooth skin in water has also been seen back in the skin of sharks: they do not have a smooth skin, they have shown to use a riblet structure which is aligned in the direction of flow. This provides a maximum drag reduction of nearly 10% (Dean and Bhushan, 2010). By decreasing hydrodynamic resistance, ALS can lead to significant fuel-savings, leading to similar 10% or even more (Khan et al., 2021). The technology is particularly beneficial for large vessels, such as bulk carriers and tankers, because even marginal improvements in efficiency will result in significant reductions in fuel consumption and CO_2-emissions. But how much energy can be saved, depends on aspects like the vessel type and operating conditions.

In terms of this, different types of vessels have a different form of hull. Study by An et al. (2022) found that bulk carriers and tankers (with flat bottom shapes) can hold more air bubbles in the hull bottom and thus are more prone to energy saving with ALS "by reducing the effective wetted surface area of the vessel through lubrication between the water flow and the hull surface". This means that the area that can be covered with air increases as the flat bottom surface of the hull increases, which consequently results in a growing potential of energy savings. The study concluded with a description of the ideal vessel type for ALS. This is a flat bottom hull shaped vessel that operates at low draft and with a low speed, typically a coastal barge.

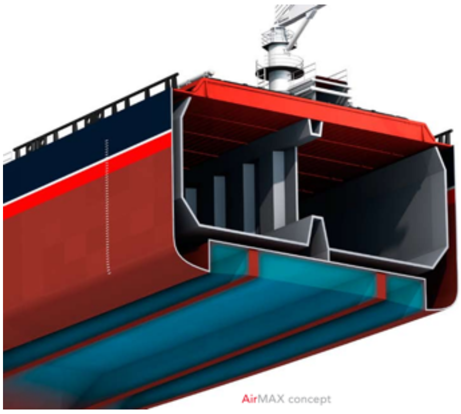

Figure 15: Air cavity by Stena (Timmerman et al., 2011)

Operation conditions also have a significant impact on the effective ALS. The effect of wind and waves even reduces energy savings by 15–35% compared to calm water conditions, taking into account the actual weather environment and the effect of weather correction (Kim and Steen, 2023). This counts for all three types of ALS that have been examined in the study. What has also been found is that all three of these ALS result in a different power saving: 2–5% from air bubble; 8–14% from air layer; and 16 to 22% from the air cavity technology. The loss of effectivity resulted by the instability of the air flow on the flat bottom of the vessel. Thus, for evaluating the effectiveness, an uncertainty analysis has been performed to simulate a real world scenario of a sea trial with the use of Monte Carlo simulations by Seo and Oh (2020). His findings showed the average power savings to be 3,2%. This is substantially lower than the theoretical amount of energy saving as given by other researches which were based on calm seas. Thus, ALS is significantly more effective in flat seas, since rolling removes the effect.

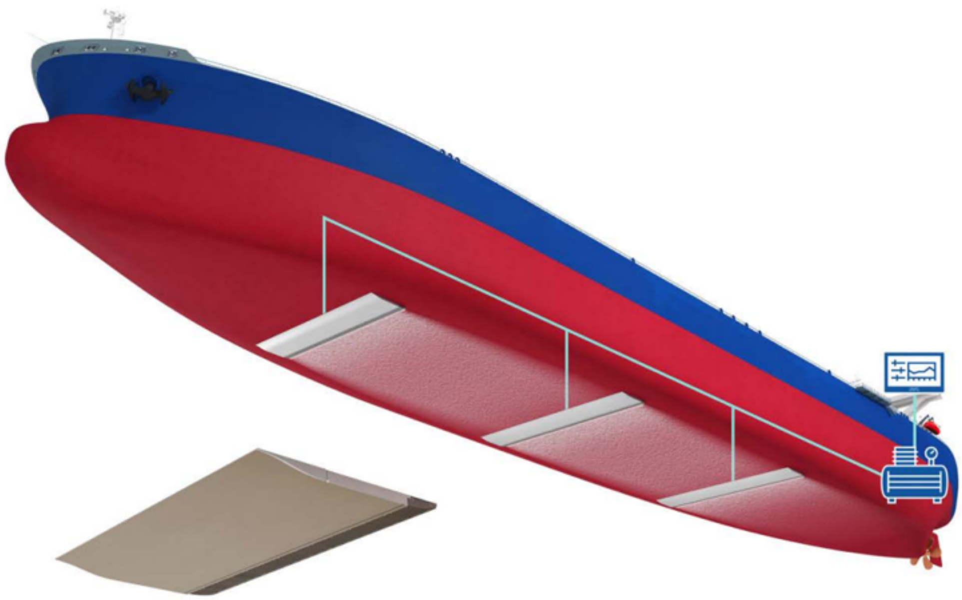

Figure 16: ALS by Alfa Laval (Laval, 2023)

Air cavity is a concept which changes the form of the hull and is thus better for newbuild vessels, as can be

shown in figure 15. It does not pass the maximum CAPEX classification criterion, which means that it is not used in this analysis. This is one which is made by Stena and is suitable for higher speeds and shallower drafts. Air layer is similar to air bubble but at a higher pressure. Air bubble works by shooting very small bubbles beneath the vessel and works better with slow-moving, very large, flat bottomed vessels, shown in figure 16. The ALS in this figure is made by Alfa Laval and this company has also been interviewed. They developed a system which costs a low amount of effort in retrofitting the vessels, since one hole has to be drilled in the hull and the glider is attached to to ships. Other companies which offer ALS require more changes to the hull and that might be more promising for new built vessels. Since the vessels which are in the scope of this thesis are existing ships, this is an important feature to take with. Further, the built-in time is two weeks and they have done it already on vessels that are actually sailing and using it (10 of them in 2024). These include vessels of 230 DWT. Also, the system is different to the competitors of Alfa Laval, due to combining the ALS with fluidics which is the control of fluid pressure and flow by means of precisely shaped channels so without any moving parts. This fluidic technology allows the creation of a distributed air layer which results in a significantly reduced compressor power that is needed (Alfa-Laval, 2023). Concluding, this innovation reduces specific drag by 50–75%. For more information, see the interview in B.4.
The type of ALS that is used in the decision support system, is this type by Alfa Laval, due to passing the classification criteria.

3.2.2 Hull cleaning

Hull coating on ocean-going vessels is an important way to reduce CO2 emissions by improving how efficiently ships use fuel. Over time, ships develop a layer of marine growth, like algae, on their hulls. This growth increases drag, making it harder for the ship to move through water. As a result, the ship's engine must work harder, burning more fuel and producing more CO2 (Townsin, 2003) (Song et al., 2019). Special hull coatings, such as anti fouling paints, prevent this build-up by creating a surface that is harder for marine organisms to attach to. Additionally, some coatings are designed to make the hull smoother, further reducing resistance in the water. With less drag, the ship requires less fuel to travel the same distance, which leads to lower CO2 emissions. By applying and maintaining these coatings, shipping companies can help reduce their environmental impact and contribute to global efforts to decrease carbon emissions in the maritime industry (Hakim et al., 2019). However, biocides in anti-fouling can also have an effect on the marine environment.

Currently: Jotun
There are different kinds of anti-fouling and anti-fouling itself has already been proven effective in the maritime sector. This is why this measure goes further: it goes into optimizing the hull performance with regard to the state of the anti-fouling. Jumbo Maritime has currently (2024) started a trial with Jotun, with (a part of) their service called Hullkeeper. This product includes a range of services that helps identify potential hull problems long before they slow the vessel down by the attachment of fouling. This allows Jumbo Maritime to make decisions about potentially cleaning the hull due to the increased friction. HullKeeper monitors the hull performance and fouling pressure by combining data. Using the data provided, the program can build an operational profile of the vessel. The service can then determine if a vessel has been exposed to a specific fouling risk, based on that operational profile. This is "done by Jotun's fouling risk algorithm which combines trade auditing periods and oceanographic parameters" (Jotun, 2024). What they also offer in their program, is an underwater inspection using a ROV if the fouling risk is considered as needing investigation. Based on the video of the hull condition, an in-depth report to the operator can be given by the Jotun specialists. Due to the fouling risk constantly being monitored, a decision on future action can be made before fouling becomes a major problem, which results in preventing unnecessary GHG emission. Note, Jumbo Maritime also uses the anti fouling from Jotun.

Chosen alternative for this thesis: Damen Hull Cleaning Service
This last aspect, is what this alternative is about: cleaning the hull of the vessel. The company that is taken as example in this thesis, is Damen (Damen, 2024). They offer a hull cleaning service which can be done afloat, which is a big advantage since no drydocking is needed. This saves time and money by taking less downtime for the vessels and thus not significantly interrupting operations. Damen uses the modern underwater robot of HullWiper, which can work 24/7. This robot cleans by spraying high-pressure seawater to remove waste without using harsh chemicals or scrubbing. The waste is then sucked up, and the polluted water is cleaned with advanced filters. This method follows all environmental rules in ports and harbors, providing a safe and sustainable solution.
Thus, fouling under the waterline can significantly impact how well a vessel performs, increasing drag and fuel use. Damen offers a modern hull cleaning service to tackle this problem. Their advanced methods can reduce

fuel consumption by up to 10%, improving efficiency and reducing costs. This can already be done in 12 hours (Cavcic, 2024). However, hull cleaning can potentially remove or damage anti-fouling coatings, especially if the cleaning method is too penetrative or not specifically tailored to the type of coating. If chosen, Damen and the coating supplier must be consulted to see if it does not decrease the anti-fouling life span too much and a schedule has to be made that balances hull cleanliness with anti-fouling durability. This ensures fuel-savings without degrading the coating too soon.

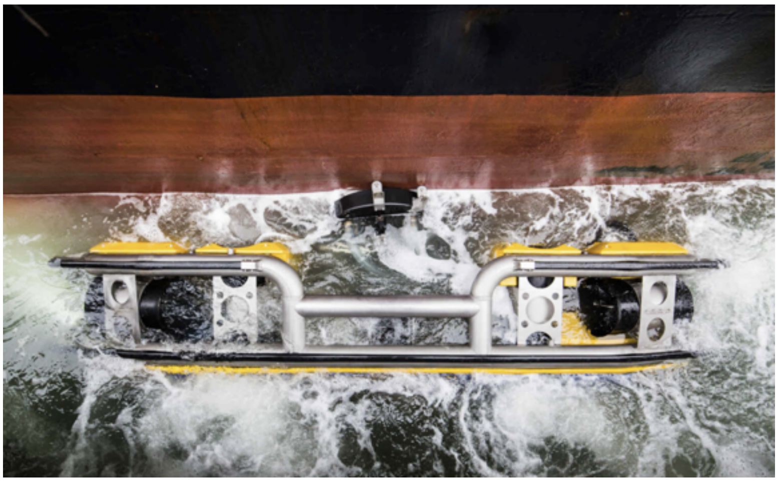

Figure 17: Hull cleaning by Damen (Offshore-Energy, 2024)

3.2.3 Flipper Zipper

The Flipper Zipper is an object which already exists within Jumbo Maritime. It is a system that is placed in the rails on the sides of a (heavy-lift) vessel. These rails are used for attaching a compensating block (pontoon) on the side of the ship in order to successfully and safely lift an heavy object on (or off) the ship. This works due to Archimedes' principle, which states: "buoyancy force on an object immersed or floating in a liquid is equal to the weight of the liquid displaced" (Naylor and Tsai, 2021). The pontoon makes the buoyant area bigger, making the vessel more stable when moving objects from and to the vessel. This means that when an object moves in water, it has to push water along with it, making it feel heavier and harder to move. Also, ballast water inside the vessel is used in this stability process. This creates the ability to lift heavy objects from and to the vessel while staying stabile.

When the Flipper Zipper is secured, the pontoon first has to be detached from the rails. Then these pontoons are used as working station to secure the Flipper Zipper to the ship. A manual is made for the attachment and removal process, depicted in the appendix A.3.

Due to the fact that the rails are located above and below waterlevel on the outside of the ship, resistance exists when the vessel is sailing. The water gets in those open rails, resulting in drag, as seen in an actual picture on a Jumbo Maritime HLV in figure 18. About 3% of the resistance can be deduced from this increase in friction, as stated by Jumbo Maritime in appendix A.3 in figure 45. To reduce/eliminate this effect, Flipper Zippers were manufactured which fill up these rails. The implementation was seeming to work, however, it took a significantly amount of time to set them up and people do not generally want to do that effort. Also, when attaching them to the quayside of the ship, the ship first needs to leave the quay, and this is also seen as a very impractical moment to lift and secure such an object for the crew. This is affecting the operational flexibility.

There are problems on wrong material but this has been solved. They did not close well, which resulted in water being able to come between the rails and the Flipper Zipper. This power, coming from sailing while water getting in between the system, bended the Flipper Zipper. The second (current) version has been repaired and fixed. However, due to the extra effort and the hassle that it gives (has given), resulted in them not being used currently.

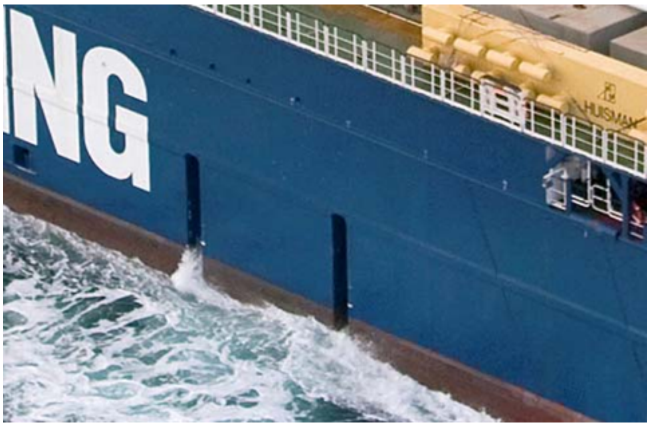

Figure 18: The rails without the Flipper Zipper (Jumbo Maritime, 2015)

3.3 Energy efficiency

The following measures are focused on increasing the energy efficiency of a vessel. This can be done via using the vortex which leaves the propellor with a Propeller Boss Cap Fin (PBCF); installing software to optimize slow-steaming in combination with a variable propeller pitch setting, called Eco-control; and using the waste heat from the exhaust gasses with heat recovery.

3.3.1 Propeller Boss Cap Fins (PBCF)

There are different possible adaptations which can be done at the propeller of the vessel. Starting with the Energopac System, which significantly reduces the friction and vibrations that result from the vortex on the rudder. This leads to the effect that less fuel is used and thus wasted. It integrates the propeller and rudder into a single optimized design to improve propulsion efficiency. By reducing rudder resistance and enhancing the interaction between the propeller and the rudder, the design can achieve power savings that range from 2% to 9% (Wärtsilä, 2023b). As with every design measure, it depends on the type of vessel and the operational profile to determine how much it will affect fuel-savings. This system is particularly useful for ocean-going vessels which want to improve their fuel efficiency and thereby reduce emissions. However, this alternative needs a complete new mechanism of the rudder, which comes out as very costly for retrofitting. It is also not been proven to result in a high TRL and needs a long installation time. Due to not passing the classification criteria TRL and being high on CAPEX, it is not used in the analysis.

Chosen alternative for this thesis: PBCF by Wärtsilä
Another option, which is relatively easy to install and equip, is the Propeller Boss Cap Fins (PBCF), which are also offered by Wärtsilä which calls it the "EnergoProFin" (Wärtsilä, 2022b). This cap is a equipped with fins which rotate alongside the propeller. This design also mitigates the propeller hub vortex, just as the Energopac System but easier, since it is just a cap that needs to be replaced (with fittings). This improves the propulsive efficiency by converting rotational energy into effective thrust and its effect is depicted in figure 19. The fin can result in fuel-savings of up to 5%, and average fuel-savings of 2%, with a payback time of less than one year. At SCG (2017), they stated to improve their fuel consumption with 3% (which is different from fuel-saving)and had a payback period with this of 9 months. This short payback period might be very attractive to certain actors. It is suitable for both newbuilds and existing vessels, it is applicable to fixed pitch propellers of any brand and controllable pitch propellers for Wärtsilä brand propellers.
Since the ROI of this concept is fast, this will be used in the analysis.

Another promising option: Propeller Coating
Anti-fouling also has a significant effect on the propeller. According to Zhang et al. (2023), anti-fouling coatings on ship propellers can make a big difference by stopping marine organisms from building up on the surface. When these organisms accumulate, they make the surface rougher, which increases drag and lowers efficiency. By keeping the propeller smoother, antifouling coatings help the ship move more easily through the water, saving fuel and improving performance. Research by Faber et al. (2011) showed even a CO_2 emission reduction of 2,5 to 8% with propellor polishing.

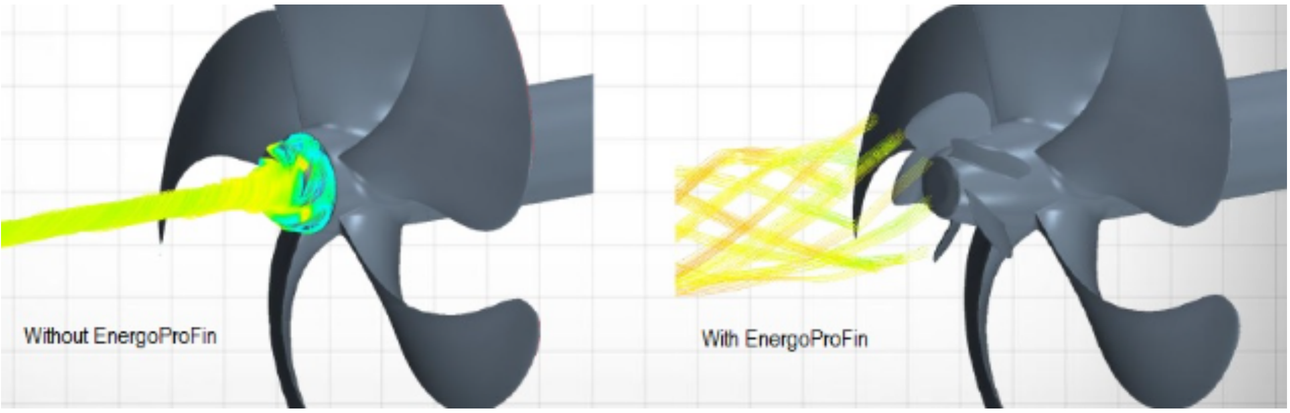

Figure 19: Wärtsilä EnergoProFin (SCG, 2017)

3.3.2 Eco-control

Eco-control is measure which is based on slow steaming, which means sailing slower than ordinary.
Traditionally, ships are often designed to operate at their hydrodynamic boundary speeds and this is the speed at which the resistance starts to rise rapidly with any further increase in speed. This depends per hull and this power requirement is proportional to the product of speed and resistance. So when a ship reduces its speed, the fuel consumption is reduced, which leads to the significant fuel reductions and with this, emission reductions. According to research by Cariou (2011), slow-steaming has proven to decrease emissions by around 11% in the years 2008-2010. This reduction has been done without the use of other fuel-saving technologies and it was observed in container ships. The motive for the slow-steaming was due to rising fuel prices, which thus result in a financial reason for reducing the use of fuel. Also when freight rates and inventory costs rise, the profit motives for operating a vessel at full speed are likely to rise. Also, reducing a vessel's speed by 10% has shown to decrease the emissions by at least 10–15% while also creating substantial losses in revenues (Psaraftis and Kontovas, 2010). The losses in revenue are due to increased time a product spends in transit, which also means that the vessel can not be used for another trip, resulting in lower time efficiency. So in short, lower speeds result in fewer emissions of CO2, SO2 and NO2, which supports global efforts towards becoming more sustainable. While slow-steaming can be challenging for time-sensitive supply chains, it makes an important trade-off between efficiency and environmental responsibility in maritime transport. It can result in 27% fuel-saving for 10% of speed reduction (Craglia et al., 2020). Thus, slow-steaming has the advantage of emitting less GHG gasses than going the hydrodynamic boundary speed. This is why a measure called Eco-control has been implemented aboard the HLV Jubilee. It aims at reducing the emission by reducing the power that is generated by the engines. This results in a reduced amount of fuel that is used by the vessel. But it also has a downside, it results in a smaller electric frequency generated by the engines and this matters. Standard, the engines produce 60 Hz which lets all the apparatus on board function properly. However, when Eco control is activated, this is reduced to 58 Hz, which is the threshold for the apparatus on board. When the engines reduce their power even more, the flow of electricity gets below 58 Hz but in order to keep the 58 Hz for the function of the ship, a converter is activated. **The pitch setting of the propeller is a variable** that influences the speed. For example, when the power is reduced, the ships goes slower. In order to keep the ship on its cruising speed (if that it preferred), the pitch of the propeller is set more rough so it moves more water at each turn. In this thesis, Wärtsilä is chosen as reference for the eco-control since Jumbo has a relationship with them and this Eco-control is specifically for retrofitting (Wärtsilä, 2023a). The installationtime is relatively quick since it is software that needs to be uploaded, however, it needs input and getting the right input for the system that is reliable and correct, it crucial for the success of the software.
The expected savings are 3-5% in fuel according to Jumbo Maritime

3.3.3 Heat recovery

Heat recovery is a key topic in the energy transition and has been widely researched. A significant amount of heat is wasted because it exceeds what is needed. Since this lost heat represents wasted energy, heat exchangers have been developed to capture and reuse it.

Here is how it works:
It starts with an internal combustion engine (ICE) converting fuel into power. When fuel is burned on a ship, only 40-50% of the energy is used efficiently, while 50-60% is lost as heat. This heat escapes through exhaust

gases, cooling systems, and other engine components. To recover some of this lost energy, exhaust heat is used to warm thermal oil, which is then directed to systems that require heat. This includes:

- Fuel tanks: Fuel must stay warm to remain fluid and flow through pipes;
- Pumps: Liquids need to stay at the right temperature for smooth operation;
- Engine room heating: Provides a comfortable working environment in cold conditions;
- Other onboard systems: Various installations benefit from recovered heat.

Despite these efforts, a large amount of heat is still wasted because it cannot always be fully utilized. This is where heat exchangers come in, helping to optimize heat distribution and reduce unnecessary energy loss. One such a manufacturer is Orcan, and two of those installations will be installed on the HLV Fairmaster and HLV Kinetic in the near future (start of 2025). In appendix A.4, the thermal oil circuit is shown and this picture is made on the HLV Fairmaster. However, because the Orcan unit uses multiple systems, the installation time is very long.
The Orcan unit, specifically the Orcan efficiency PACK eP M 150.200, can be retrofitted aboard ships and can produce up to 200 kW net electric maximum rated output per module. The dimensions are 2,200 x 1,650 x 2,060 mm (W x L x H) and it can use the following heat sources for the heat exchange:

- Exhaust gas (max. 600 C);
- Saturated steam (120–180 C)
- Thermal oil (120–180 C)
- Warm water (e.g. from jacket cooling, 75–109 C)

In the HLV's of Jumbo Maritime, thermal oil is thus used for the production of electricity for the ship by the Orcan unit. This heat exchanger works by letting a certain gas (freon) evaporate which transfers the heat into the efficiency PACK. In this process, the pressurized gas is first heated and directed towards the expansion machine. Here, the vaporized fluid powers the expansion machine, which then drives the generator to produce electricity. Afterward, the vaporized fluid is condensed in the condenser, releasing any remaining heat into the surrounding air. The fluid, now in liquid form again, is pressurized by the pump, completing the cycle and allowing it to restart. This process is also shown in figure 20.
When using the Orcan unit, different fuel types results in different amounts of electricity productions by the machine. If biofuel is used for example, less heat is needed for prewarming the fuel. This measn more waste heat remains which can be used by the heat exchanger.
The Orcan unit shows that it is an innovative energy efficiency solution designed to reduce fuel consumption, and thereby emissions, in vessels by using waste heat. By using this unit, the auxiliary engine is not needed for power production when sailing. Sidenote, the shaft generators (which are installed on every ship owned by Jumbo Maritime) also generate electricity which is used on board. **The expected saving due to the Orcan unit are put on 135K USD/year.**

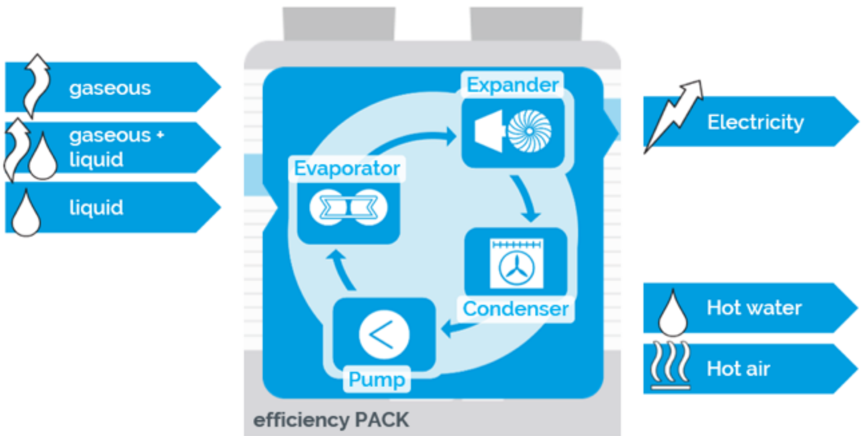

Figure 20: Orcan unit (Orcan, 2024)

3.4 Fuel

This thesis only focuses on alternative fuels which can be used with the existing engines aboard the vessels of Jumbo Maritime. These are VLSFO, MGO and biofuels. Otherwise, the vessels need retrofitting and that is out of the scope.
When working in projects or jobs for clients, fuel choice is also important. Some fuel types may be less expensive and more efficient, but emit too much emission. In a conversation with a purchaser (who also decides which fuel to bunker) within Jumbo Maritime, it became evident that the fuel choice is more difficult than it would be expected initially. He also showed one of the information sources he used in the trade-off for which fuel to bunker, as seen in figure 21. The price per energy is variable with the kind of fuel as well as the CO2 emission factors. The percentages after some fuel types refer to the SOx amount of the fuel, which is relevant for the ECA. The ECA is a regulation by the IMO which goes into areas where a SOx cap exists, explained in appendix A.7.
In the following sections, the three different options for fuel types are described. Note that these are all possible to use in the DSS.

Product	Supply	Prices				CO2 Emission factors**			
		Per unit		Per energy		WTW*	TTW*	WTT*	Unit
VLSFO 0,5%	Delivered	USD	588,00 MT	USD	0,01470 MJ	3,762	3,110	0,652	KG CO2/ltr
HFO 500 CST 3,5%	Delivered	USD	518,00 MT	USD	0,01328 MJ	3,762	3,110	0,652	KG CO2/ltr
HFO 380 CST 3,5%	Delivered	USD	522,00 MT	USD	0,01338 MJ	3,762	3,110	0,652	KG CO2/ltr
RMD 80 0,1%	Delivered	USD	747,00 MT	USD	0,01822 MJ	3,762	3,110	0,652	KG CO2/ltr
Gasoil 0,1%	Delivered	USD	780,00 MT	USD	0,01857 MJ	3,468	2,652	0,816	KG CO2/ltr
ULSD 10ppm EN590	FOB Barge	USD	811,00 MT	USD	0,01890 MJ	3,256	2,468	0,787	KG CO2/ltr
GTL	Delivered	USD	878,16 MT	USD	0,02014 MJ	3,268	2,465	0,803	KG CO2/ltr
LNG	Delivered	EUR	40,41 Mwh	USD	0,01380 MJ	3,651	2,945	0,706	KG CO2/KG
Methanol	FOB Cargo	USD	374,76 MT	USD	0,01874 MJ	***	***	***	***
Biodiesel 100% HVO	Delivered	EUR	1150,00 CBM	USD	0,03579 MJ	0,347	0,032	0,314	KG CO2/ltr

** WTW: Well to wheel (total impact)*
** TTW: Tank to wheel (impact of use)*
** WTT: Well to Tank (impact of production)*
*** Source: www.co2emissiefactoren.nl*
**** CO2 Emission factors Methanol not available yet*

Figure 21: Fuel prices July 2024 (Bebeka, 2024)

3.4.1 VLSFO

VLSFO stand for Very Low Sulphur Fuel Oil. This fuel type contains 0,5% of SOx when emitted, which is above the ECA limit of 0.1%. When sailing outside of ECA, this fuel can be used for sailing since it is not exceeding the global level of 0,5% of SOx. This shows that it is complying with the IMO's (global) regulation of 2020 and that it is a step towards a lower-emission shipping (IMO, 2021). However, it does not address GHG emissions as it still releases a fair amount of CO2 in the air when burned. Further, it has become the preferred choice for many shipping companies due to its lower fuel cost compared to MGO and its less complex implementation compared to fitting scrubbers (Casey, 2024).

3.4.2 MGO

MGO, Marine Gas Oil, is a fossil fuel type which often emits a lower amount of SOx than VLSFO. It is more refined and thus more expensive than VLSFO, this is also shown in figure 21. It is a distillate fuel which means it is produced through the distillation of crude oil. More specifically, MGO is a middle distillate, meaning it is produced between diesel and HFO. It naturally has a low SOx content, very often below 0.1% of SOx but always below 0.5%, which makes it compliant with even stricter SECA (Fuels, 2024). Since MGO generally has a SOx amount of 0.1%, this is also written next to the fuel, as can be seen in figure 21.

3.4.3 Bio-fuel

Biofuel is an emerging and promising alternative fuel for the maritime sector. It is renewable, derived from organic materials, and it can be used in (most) conventional engines, which leads to a smaller financial barrier since real retrofitting is not necessary. Bio-fuels do generally not emit any SOx and a lot less GHG than fossil fuels over their life-time, which leads to it being very interesting for the future of the maritime sector. However, the biofuel has to come from a green origin in order to stay a green fuel. But, as a rule of thumb, biofuels can reduce overall CO2 emissions by something in the region of 40–80% from a well-to-wake

perspective (Wärtsilä, 2022a). If the production process of biofuel emits a lot of CO2 for example, it does not make sense to switch to biofuel since its goal is to decrease emissions.
Additionally, biodiesel reduces the annually reported CO2 emissions for EU MRV. But since biofuel is still being on the rise, and it is very diverse in how it is produced, it is very fluctuating in price. These fluctuations are also due to the changing demand and supply: it is not rarely seen that these manufacturers collapse due to this unstable market.
The following types exist:

- FAME (Fatty Acid Methyl Ester), also called **biodiesel**, is biofuel which is produced from vegetable oils, animal fats or waste cooking oils by transesterification. This is a process where oils or fats are reacting with methanol and by this are converted to methyl esters. FAME is the most available type of biodiesel in the production for the maritime industry. The biofuel is often blended with regular marine diesel, which results in lower emissions from those original fossil fuels. These ratios can be B15, so 15%, until even B30, or 30%! A lot of testing is also being done with this fuel and its potential for lowering the emissions. For example, TNO (2024) is now (2024) doing tests with eight ships in the Netherlands and they find a decrease of 26% CO2 (when using B30) compared with MGO. The disadvantage however, is that the endproduct is oxygenated biodiesel, which makes it less stable and more prone to oxidation and water absorption.
- HVO (Hydrotreated Vegetable Oil), also called **renewable diesel**, is the product by using fats or vegetable oils (alone or blended with petroleum) and it is produced by using hydrogen to treat waste oils and fats to create a stable, oxygen-free fuel. It results in a higher quality fuel with properties that are closer to traditional diesel. The overall production process of HVO is typically more costly than for FAME, however, the big advantage is that HVO is a fuel type which can be directly used in the distribution and the refueling facilities as well as existing diesel engines without any modification (DNV, 2020). This fueltype does not contain oxygen and is thus more stable than FAME. Companies like Goodfuels (a prioneer in offering HVO), offers HVO and state that using their HVO in marine vessels results in a reduction of CO2 emission up to 90% (Goodfuels, 2024).
- BTL (biomass to liquid fuels) is a synthetic biofuel which is produced from biomass by using thermo-chemical conversion. The end fuel product is chemically different from the conventional fuels but it can also be used in conventional engines. However, the price of BTL is typically even higher than the other biofuel types (Piltan, 2023).

By promoting sustainable fuels like HVO, GoodFuels exemplifies how innovative energy solutions can drive decarbonisation without compromising performance or reliability. However, it comes at a higher price and the biofuel availability is not as reliable yet, which makes it harder to adopt.

3.4.4 HSFO

Higher Sulfur Fuel Oil (HSFO) have higher dosages of SOx, like HFO. These can be used by vessels if only they have a EGCS, or scrubber, installed. This scrubber is designed to filter the SOx out of the exhaust gases. The result is that the SOx limit is not exceeded, which is compatible with the ECA. This is the maximum global SOx emission of 0.5%, as can be seen again in figure 49. But since the vessels of Jumbo Maritime do not have a scrubber installed, these HSFO are not part of the trade-off and thus they are discussed no further in this thesis. Of course, scrubbers can be installed aboard the vessels, but since this thesis only focuses on decreasing the emission of GHG (and SOx is not a GHG), that falls out of the scope. Also, scrubbers are very expensive.

3.5 Alternatives not included but relevant

The following measures which reduce emissions are not included due to their own reasons. In order to be complete and due to their relevance, they are still included in this chapter.

3.5.1 Smart Scheduling

Smart Scheduling is an advanced way to plan a trip in order to efficiently use fuel and time. In multiple thesis' done at Jumbo Maritime by graduation students this has been researched. For example by a TU Delft master thesis of Lanphen (2015) who found that at the time, there was a lack of suitable commercial scheduling tools which led to manual scheduling by the commerce department. As a result of this manual scheduling, "poor schedules were obtained with deadlines that theoretically cannot be achieved". Also, which led to commerce

being optimistic, was the risk of losing an inquiry to competitors with a faster scheduling process. However, in order to improve this problem, in 2021, Smart Scheduling was implemented within Jumbo Maritime. This program lets different departments within Jumbo Maritime input data in order to create more reliable historical data for trips. This historical data includes port costs, loading costs in the ports and sailing time. In this way, the commerce department can give more accurate prices to the potential client and with an increasing amount of data, increasing more reliable estimates can be given. This is also the job of the commerce department: they sell time and space aboard the vessels. How more efficiency this happens, the better for the financial outcome of the project.
In another program, called **We4Sea**, the vessels input the real-time data of the trips they are making, which leads analysis of the trips. This analysis goes into how much fuel the vessel is using, and compares this with how much it uses in an ideal case, in which the ships hull is totally clean for example. A model of this ideal trip is running, as a so-called digital twin, which makes it possible to see how innovations (like WASP) are performing, which is especially relevant seen the scope of this thesis. But also, it is used for making a trade-off on when to dock a ship in order to clean it. Because how cleaner the ship is, the more efficiently it can sail. Note, these two applications (Smart Scheduling and We4Sea) are used already by all the vessels. This is why these are not used in the DSS as an alternative. However, it is useful for acquiring scores for measuring (input for the performance matrix in this thesis) on how well alternatives score.
Concluding, Jumbo Maritime has shown to embrace digitization with increases their operational efficiency.

3.5.2 Carbon Capture and Storage

Carbon Capture and Storage (CCS) is a measure that takes CO2 from exhaust gases and stores it in a separate tank. This tank has to be unloaded at a port in order to be emptied in an environmentally friendly way. However, this technology is not feasible on trips made by Jumbo Maritime. This is the case because Jumbo Maritime sails around the whole world and not nearly all of the port where there is berthed, there is no infrastructure to support this. This means that if it is not possible to drop the filled carbon capture tank, it has to stay aboard. When this happens, this will result in less available deck space for the job. However, the carbon capture tank will result in the loss of free deck space, which is a very restricting factor in their area of expertise. However, when ships are frequently sailing between the same ports or when they know they can certainly unload full carbon capture tanks, it has a benefit. But in the case of Jumbo Maritime, it does not: this means that carbon capture is excluded from the analysis. Maybe if the TRL becomes higher in the form that the space needed is smaller, and if the availability to drop the tanks off is higher, than it might be a valuable option.

3.6 Conclusion

Eight alternative measures, that decrease GHG emission, have been described. As can be read, each of these has pros and cons. These are also used and described in the analysis of the alternatives, seen in appendix A.11. Summarized, the pros and cons are listed below:

Measure	**Pros**	**Cons**
WASP	Reward factor for FEUM, great potential for fuel-saving.	Expensive, effectiveness depends on external power (wind power and apparent direction).
Wavefoil	Retractable, renewable power by the waves, innovative.	No proven track record for oceangoing vessels, expensive, effectiveness depends on external power.
ALS	Can result in significant fuel-saving, widely researched.	Expensive, effectiveness depends on the environment and hull.
Hull cleaning	Fast procedure, relatively cheap.	Might degrade certain types of anti-fouling.
Flipper Zipper	Already existing, cheap.	Big impact on crew operations.
Propeller Boss Cap Fins	Easy to implement, fast ROI.	Must be tailored to the specific propeller and vessel.
Eco-control	Proven technology, fast installation.	Dependent on data quality, relatively high initial investment.
Heat recovery	Proven concept and high CRI.	Very long installation time.

Table 3: Comparison of measures that decrease GHG emission

4 Methodology

The question on which sustainable measure fits the HLV Fairmaster the best, requires an extensive analysis. The end product is a Decision Support System (DSS) which can be used to evaluate different alternative measures and which gives useful output. This process towards a well-working DSS, has been divided into four main steps which use different methods. In this system, the HLV Fairmaster is taken as the initial input with the use of a case-study. The measures that reduce the GHG emission are described in this chapter, just as the different fuel types which can be used for the existing engines. The change of the output with reduced emission shows how well different alternatives work. In this section, first the four steps are described; then an table is given with the methods and where they are used for; then the main methods are analyzed with their pros and cons; followed by the stakeholders which are deemed as relevant for this research. Lastly, the different alternatives are presented in this chapter.

4.1 Four steps towards a complete Decision Support System

In this thesis, the process in getting an answer to the main research question can be divided in four steps. The process can also be seen in the Gantt-chart which is depicted in section 8, figure 39, but visually it is shown (with the corresponding methods) below in figure 22. The content of the box "Decision Support System" in the figure, is described in section 4.6.

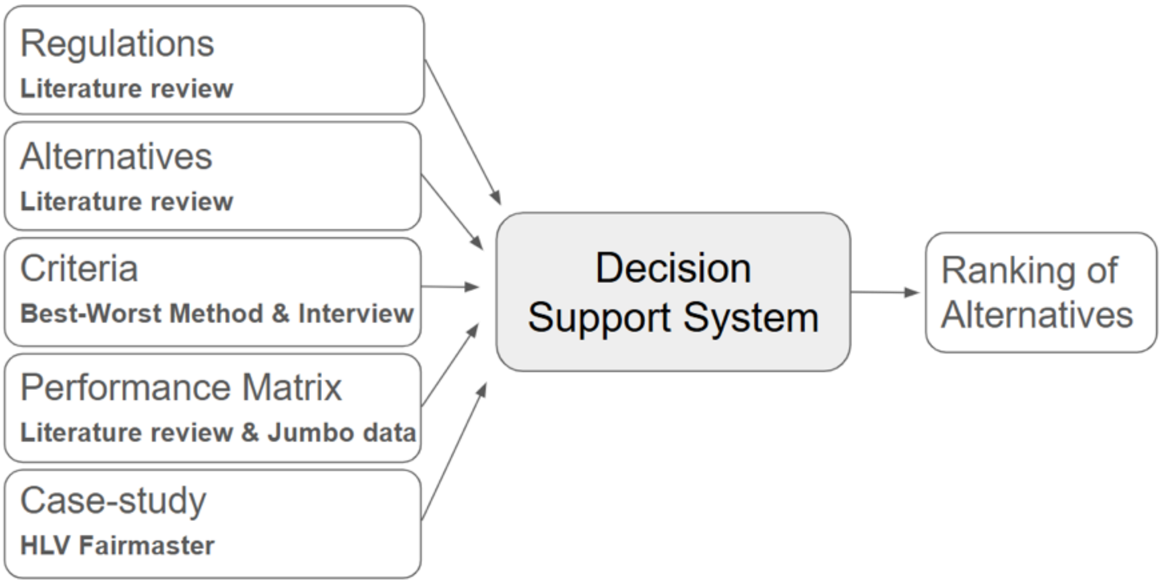

Figure 22: Visually representation of the input of the Decision Support System (Figure made by author)

4.1.1 Step 1: Information gathering

First, the problem of Jumbo Maritime must become structured. In order to do this, a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) was executed, as described in 1.5. DNV is the input of the external Opportunities and Threats together with literature research, Jumbo Maritime is the input for the internal Strengths and Weaknesses. The main research question and the sub research questions conclude the problem overview since they emerge from the shown research gap. This information is gotten via Jumbo Maritime, DNV and a literature review.

Then the biggest step of this thesis: the input of the DSS. This is divided in three parts: regulations, alternatives, and the relevant criteria.

- The regulations entail the environment in which the GHG decreasing measure will show its effect. This includes the EU regulations and the IMO directives. This includes what the current state is of the relevant regulations of the EU and the IMO. This is done via a literature review and this is shown in section 2.2. Different search engines shall be used, like Google and Google Scholar, but only reliable sources (like the IMO and European Commission find their way into this thesis.

- The possible alternative measures are next. This includes an overview of these alternatives and a description of what they entail. This is given in section 3 and these alternatives come from literature review and Jumbo Maritime.
- The criteria of Jumbo Maritime are also examined. This will be done via interviews with different departments of the company which are relevant in the decision making process and in the success of the implementation. These are acquired by the different managers, given in section 4.3.

4.1.2 Step 2: Model building

The decision support system has multiple sources of input, as described in Step 1. The next step is filling the performance matrix and weighing the criteria.

- Starting with filling the performance matrix, this shows how the different alternatives score on the HLV Fairmaster with regard to the criteria. The criteria stems from Step 1 as well as the selected number of alternatives. The performance matrix is filled with scores that are obtained via various parties and literature research. These parties might be manufacturers of different measures, from models made in house by Jumbo Maritime, from interviews conducted with manufacturers, experts within Jumbo Maritime and external experts.
- The criteria also need to be weighted according to their relevance and importance. These weights of the different criteria result from a multi-criteria decision method (MCDM). A MCDM is necessary since it is made to handle complex problems (or decisions) with multiple criteria. The number of criteria that play a role, result from the semi-structured interviews conducted on the relevant department managers from Jumbo Maritime. The chosen MCDM is the Best-Worst Method (BWM). The input for this method comes from a structured interview which was conducted the board of directors from Jumbo Maritime, since they are the ones who make these decisions and deliver input for those decisions. In section 4.2.4, this has been described in depth.
- A concise case-study is done on the HLV Fairmaster to get input for the decision system. This includes the physical characteristics of the vessel like the length and operational characteristics like the time it sails in European waters.

The end-goal, the decision support system, combines the output from the performance matrix and the BWM while using the input from the case-study.

4.1.3 Step 3: Verification and validation

The DSS may be working, but it is working like it is supposed to be working? This is what will happen in this step: the validation and verification. Validation will consist of checking whether the DSS measures what it is supposed to measure. Checking this will consist of a sensitivity analysis. This will be followed by the verification of the DSS, thus checking whether it behaves correctly and logical.

4.1.4 Step 4: Interpreting the output

The results that come from this DSS, need to be interpreted in order to be useful. This consists of, primarily, by translating the results from an abstract output to a useful economical output. The shareholder and the executive management of Jumbo Maritime has to have a clear and structured picture of what has happened and what the results mean. This includes what this means in a financial way, since this is what a company is aiming to do: make as much profit as it can, while complying with the relevant regulations. A Marginal Abatement Cost Curve (MACC) is used in this step.

4.2 Methods

In this subsection, the mainly used methods are described. In table 4, an overview is given of these used methods.

Step	Method	Goal
1	SWOT	Structure the problem
1	Literature research	Gathering information about regulations
1	Literature research	Gathering information about alternative measures
1	Interview	Find criteria for performance matrix
2	Literature research & Interview	Find scores for performance matrix
2	Survey	Find trade-offs between criteria
2	MCDM - BWM	Calculate weights of criteria - Input DSS
2	Case-study	Input for the DSS
3	Extreme values	Verification
3	Sensitivity analysis	Validation
4	MACC	DSS interpretation

Table 4: Methods used in thesis

4.2.1 Interview

The interviews will be conducted with various experts and organizations, using a combination of semi-structured and structured approaches, depending on the objective of each interview.

- Semi-structured interviews have the advantage of being flexible, by combining predefined questions with the opportunity to explore new topics that arise during the conversation. For example, when interviewing a superintendent at Jumbo Maritime, general questions will be prepared in advance. However, as the discussion unfolds, new insights may arise, which generate follow-up questions to better understand their preferences and priorities. This method is useful for identifying important decision criteria that might not have been initially considered.
- Structured interviews, on the other hand, have a fixed set of questions to make sure consistency exists between responses. This approach is especially useful for gathering input for the Best-Worst Method (BWM), where the interviewees are asked to rate and compare specific criteria. Their responses provide numerical values that help determine the relative importance of each factor, generating weighted scores for the decision-making model. By using a structured format, these interviews make sure that all key trade-offs are considered systematically, in order to guarantee objective conclusions. They only have to focus on the criteria, nothing else.

Both interview types play a crucial role in the research: semi-structured interviews help explore qualitative insights, while structured interviews provide the necessary quantitative data for decision modeling. This gives a complete and consistent overview of the relevant criteria.

4.2.2 Literature review

Literature review is done with Scopus, Google Scholar and the regular Google. The information comes primarily from the first two academic resources. However, in order to find up-to-date knowledge or in order to develop knowledge on the market, for example, regular Google will be used. Information from Google will be analyzed carefully, though, since information on the internet is not verified/checked, and thus might not be up-to-date anymore, might be not reliable or might be simply incorrect. Academic sources are much more reliable because they are checked. Information that stems from verified organizations, like the IMO and the European Parliament, is also considered reliable (if they are up-to-date).

4.2.3 Case-study

The case-study method focuses on a specific object, which in this thesis is the HLV Fairmaster. This vessel serves as the primary input for the decision support system, with key characteristics such as length, power, fuel consumption, and the percentage of time spent in European waters being analyzed. The advantage of using a case study is that it allows for a practical evaluation of different GHG reduction measures on an actual Jumbo Maritime vessel, providing a more tangible understanding of their real-world impact. This results in a relevant use and testing of the DSS.

To assess how each alternative affects specific criteria, data is gathered from multiple sources, including the HLV Jubile (where various sustainable measures have already been implemented) internal research within Jumbo Maritime, and relevant literature. Additional details on the case study can be found in appendix A.16.

Characteristic	Value
Year Delivered	2013
Length O.A.	152.60 meters
Beam O.A. (Hull)	27.40 meters
Draft	8.1 M
Free Deckspace	3,250 square meters
DWT	14,000 tons
Cranes	2 * 1,500 tons capacity by Huisman
Time sailing in European waters (2019-2024)	52%

Table 5: Main characteristics of HLV Fairmaster

Characteristic	Value
Fuel type(s) 2022-2024	VLSFO & MGO
Fuel usage 2022-2024	4851,60 mt VLSFO & 360,94 mt MGO & 0,0 mt biodiesel
Days sailing (24-hour days) 2022-2024	208,18 days
Distance (AIS) 2022-2024	57822,62 nautical miles
Fuel price VLSFO	500 USD (Bunker, 2024)
Fuel price MGO	639 USD (Bunker, 2024)

Table 6: Fuel characteristics of HLV Fairmaster

4.2.4 BWM

In this thesis, the main research question is which measure to implement aboard HLV in order to decrease the GHG emissions. Here, a number of different criteria play a role, as has been found out by interviews and by the reviewing of literature. These criteria are used to find the best measure for a specific vessel by making a decision when taking all these criteria into account. This decision making process is also called Multi-Criteria Decision Analysis (MCDA). These different identified criteria need to be analyzed and weighted in order to use them accordingly. In MCDM, there are multiple methods that can be used for all kinds of decisions, and each of them has pros and cons.

The approach must be systematic in order to evaluate alternatives when decisions involve multiple (conflicting) criteria. The MCDM that is chosen for this process, is the BWM and just like every method, this method also has its pros and cons. MCDM are methods which are used for evaluating a number of alternatives with respect to a number of criteria in order to decide over the best alternative(s). The goal of the BWM is to generate accurate and robust weights for these different criteria (Rezaei, 2015). It is a decision-making tool that gives simplicity and efficiency by requiring fewer comparisons than other methods like AHP, which reduces the amount of decisions that the decisionmaker has to make (Mi et al., 2019). It also leads to more consistent judgements and checks for this consistency (Rezaei, 2020). However, it relies on subjective judgements, which can introduce bias. But this is a problem which is the risk at every MCDM. But, compared to other MCDM, it is less prone to anchoring bias (Rezaei et al., 2022). But still, when decision-makers struggle to confidently select the best and worst criteria, it stays sensible to subjectivity. Methods like AHP have shown to be worse in subjectivity (Liu et al., 2021). Also, due to fewer comparisons being necessary, this is also a risk because in more complex problems, finer distinctions may not become visible. Additionally, BWM assumes the independence of criteria, which may not always be the case in real-world situations (Tavana et al., 2022).

Compared to single vectoring methods

The Best-Worst Method (BWM) provides more accurate and consistent results compared to single-vector methods due to its structured comparison process and its ability to minimize inconsistencies. In methods such as the Weighted Sum Model (WSM), decision-makers assign weights directly to criteria or alternatives, a process that becomes increasingly unreliable as the number of criteria grows. Human judgment is inherently prone to inconsistencies, especially when multiple factors must be balanced simultaneously. Direct weight

assignment in such cases often lacks robustness, leading to inconsistencies that can significantly impact decision outcomes.
BWM addresses these challenges by reducing the number of required comparisons and structuring the decision-making process around the selection of the most and least important criteria. By focusing on these key reference points (best and worst), BWM simplifies the evaluation process, making it both more intuitive for decision-makers and more resistant to cognitive biases. Furthermore, its optimization model systematically calculates weights while minimizing inconsistencies, ensuring a higher degree of reliability. As a result, BWM produces more stable, logically consistent, and robust weight distributions compared to methods that rely solely on direct weight assignments.

How it works
The BWM has a specific steps, as described below, adopted from Rezaei (2015) and Rezaei (2016):

1. The decision-maker first chooses the most important criterion, which is the so-called "best", and the least important criterion, the so-called "worst". It is important to note that no comparison is made at this stage.

2. When these are chosen, the pairwise comparison starts in which the preference of the best criterion over all the other criteria is determined. This results in the so-called Best-to-Others (BO) vector. In this comparison, a Likert scale is used from 1, being equal important to the other criterion, to 9, being extremely more important than the other criterion.

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$$

   where a_{Bj} represents the preference of the most important criterion B over criterion j.

3. Next, the preference of all the criteria over the worst criterion is determined by using a number between 1 and 9. This results in the Others-to-Worst (OW) vector. This process reduces cognitive load and ensures more focused and reliable inputs by focusing on those two criteria only.

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$$

   where a_{jW} indicates the preference of the criterion j over the worst criterion W.

4. What follows, the calculation of the optimal weights by formulating a problem. The objective of the problem is to find a solution for minimizing the maximum absolute differences

$$|\tfrac{w_B}{w_j} - a_{Bj}| \quad \text{and} \quad |\tfrac{w_j}{w_W} - a_{jW}|$$

   for all j is minimized. This optimization model is depicted in figure 23.

$$\begin{aligned}
&\min\ \xi^L \\
&\text{s. t.} \\
&|w_B - a_{Bj} w_j| \leq \xi^L, \text{ for all } j \\
&|w_j - a_{jW} w_W| \leq \xi^L, \text{ for all } j \\
&\textstyle\sum_j w_j = 1 \\
&w_j \geq 0, \text{ for all } j
\end{aligned}$$

Figure 23: The optimization model used to find the optimal weights (Rezaei, 2016).

5. However, the comparisons must be consistent. For example: if the decision-maker rates the best criterion to be moderately more important (score 3) than criterion X and strongly more important (score 6) than criterion Y (in the best-to-others comparison); and then rates criterion X to be moderately more important (score 3) and criterion Y strongly more important (score 6) than the worst criterion (the other-to-worst comparison), that is not consistent. This makes criterion X seem indirectly more important than criterion Y in the best-to-others comparison, in contrast to the other-to-worst comparison.

   To make sure that this does not happen, a pairwise comparison consistency ratio (CR) is calculated which shows if it is acceptable or not. Of course, it does not has to match perfectly, but it needs to stay consistent, as shown by the consistency ratio. With the five criteria, it depends on the scale what the consistency threshold can be. In the structured interview with the COO and the CEO, it was until five, leading to a threshold of 0.2306. In the interview with the CFO, a scale until 7 was used, leading to a consistency threshold of 0.2819. The CR is between 0 and 1. The lower the CR the more consistent the comparisons, hence the more reliable results.

The comparison is fully consistent when $a_{Bj} * a_{jW} = a_{BW}$ for all j, where a_{Bj}, a_{jW}, a_{BW} are respectively the preference of the best criterion over the criterion j, the preference of criterion j over the worst criterion, and the preference of the best criterion over the worst criterion. The formulation is shown in figure 24.

$$CR^I = \max_j CR_j^I$$

where

$$CR_j^I = \begin{cases} \frac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1 \\ 0 & a_{BW} = 1 \end{cases}$$

Figure 24: The Input-based Consistency Ratio CR as formulated by Liang et al. (2019).

4.2.5 Sensitivity analysis

A sensitivity analysis is crucial for validating the DSS. This analysis evaluates how changes in input parameters, such as capital expenditure (CAPEX), operational expenditure (OPEX), fuel-savings, or regulatory savings, affect the tool's output recommendations. Given the variability and uncertainty in maritime operations, such as changing fuel prices, regulations that get stricter, or technological performance with regard to fuel-saving percentages, sensitivity analysis makes sure that the tool is robust and reliable under different scenarios. By identifying the parameters that most influence the decision-making process, stakeholders can better understand the risk and resilience of their choices. Furthermore, sensitivity analysis enhances the tool's credibility by demonstrating that its recommendations are not overly dependent on uncertain or subjective inputs, thereby providing confidence in its ability to guide investments in GHG reduction measures effectively.

4.2.6 MACC

A Marginal Abatement Cost Curve (MACC) is a tool which is used to evaluate the cost-effectiveness and potential impact of various measures to reduce GHG emissions. It visually shows the cost per ton of CO2-equivalence that is reduced (on the vertical axis) and the cumulative emissions reduction potential of different abatement measures (on the horizontal axis). Each bar in the curve represents a specific measure, with the width showing the emissions it can reduce and the height showing the cost per ton of emissions reduced. Measures are arranged from the most cost-effective (lowest cost per ton) on the left, to the least cost-effective (highest cost per ton) on the right. This allows to see their economic efficiency. It is useful to do a MACC next to the ordinary analysis because it gives a alternative view. The MACC also uses the CAPEX, but annualizes this over the measure's lifetime. This allows the cost-effectiveness of measures to be compared fairly, regardless of the investment cost or operational timeline.

The MACC also helps to identify "low-hanging fruit" or "the biggest bang for the buck" in emissions reduction. In this analysis, every measure came out to have negative-cost over its life-time, which means that they are very cost efficient. These energy efficiency improvements reduce emissions while generating financial savings, because savings equals negative cost. On the other hand, measures with positive costs, such as renewable energy installations or carbon capture technologies, require big investments but may be essential to achieve big emissions reduction targets, these are logically not "low hanging fruit". By quantifying the costs and benefits of each measure, the MACC enables to make informed decisions by balancing trade-offs to meet the climate goals in the most cost-effective way possible.

It is calculated by following these steps:

1. Emission reduction per alternative in ton CO2-eq/year;
   Calculating the emission reduction by converting the emission reduction per used fuel type to CO2-eq with the appropriate CO2 emission factor.
2. Annualized CAPEX discounted;
   Discounting the CAPEX with the discount rate over the lifetime of the alternative.

3. Annualized OPEX discounted;
   Discounting the OPEX-savings (which consists of fuel-savings, ETS savings, FEUM penalty savings, minus the OPEX).

4. Net annual cost;
   Summing the discounted CAPEX and OPEX-savings per alternative.

5. Generating the MACC;
   Dividing the net annual cost by the emission reduction per alternative and ranking the MAC values of the alternatives. This ranking makes the curve.

4.3 Stakeholders

To gain more insight into how to select the optimal measure that decreases the emission of GHG, the relevant stakeholders have to be known. From these stakeholders, different criteria will become evident in what they think is important in the selection of which measure to implement. These stakeholders can be divided into internal- and external stakeholders. Internal stakeholders are stakeholders from within the organization, which in this case is Jumbo Maritime. External stakeholders are the relevant actors which might have influence on making Jumbo Maritime more sustainable, or actors who might be influenced by this.

4.3.1 Internal stakeholders

As stated, the internal stakeholders are the stakeholders from within Jumbo Maritime. These are all the actors that are influenced or those who influence the decision on which measure to implement aboard the vessels, resulting in reducing the GHG emission. These stakeholders are found by using the organizational chart of Jumbo Maritime, depicted below in figure 25, in which the top layer is seen. This chart of Jumbo Maritime is last updated on 10 June 2024. The sustainability manager has started after this date, this is the reason why he is not yet implemented in the graph. He is stationed however directly below the CFO. Not every department (manager) is impacted by implementing a measure, using logic and discussion with the technical manager, the list below has emerged.

- Supervisory Board: Makes the biggest decisions regarding how much to invest in certain goals, like sustainability;
- Board of directors: Responsible for setting sustainability goals and ensuring they are integrated into the companies overall strategy, also in terms of financial goals.
- Operations Department: Supervises and manages the day-to-day operations.
- Technical Department: Focuses on fuel efficiency, emissions reduction and technology upgrades.
- Commercial Department: Focuses on the managing, coordination and supervision related to shipping activities and building, maintaining relationships with clients;
- Sustainability Manager: Focuses on the actions that reduce emissions and in charge of structuring the information that reaches the board of directors;
- Crew: Operate the vessels and must adopt sustainable practices on the ground, including efficient navigation and fuel use management.
- Partner-companies: SAL and Intermarine are partners of Jumbo Maritime and can be used for pooling in the FEUM regulation.

4.3.2 External stakeholders

The external stakeholders are all the actors that influence or those who are influenced by implementing a new measure aboard the vessels. This list has been made with the help of DNV and literature review (Strandberg-Consulting, 2019).

- Advisory companies: Like DNV, which consult and help companies in their decisions.
- General Population: This group demands sustainable innovations in shipping through their purchasing decisions and expectations for eco-friendly goods transport, also they are victims of climate change.

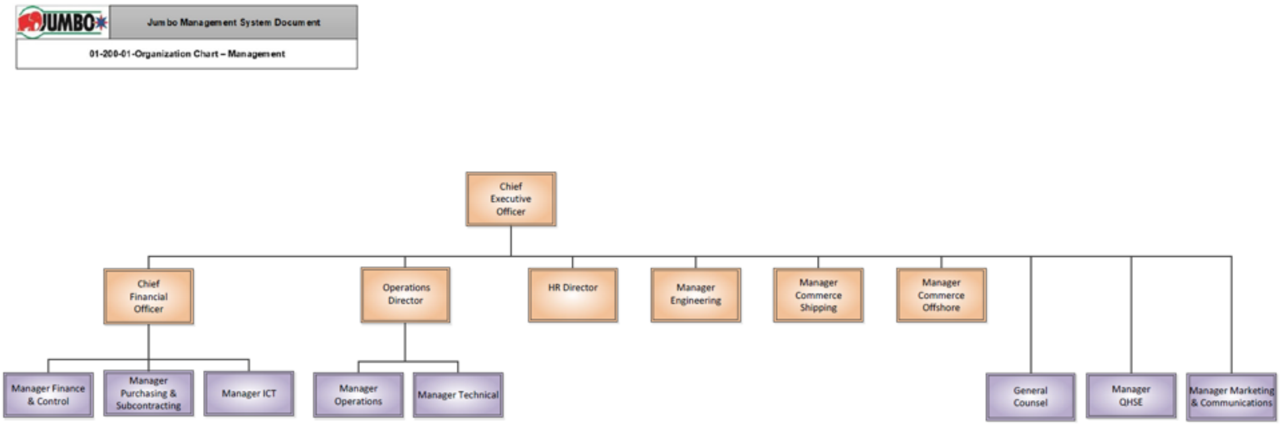

Figure 25: Organizational chart top layer

- Shipbuilders: They build and retrofit vessels to become more fuel-efficient by using emission reduction technologies and innovations like alternative fuel systems.
- Policymakers and regulators: Governments and organizations like the IMO and EU that set environmental regulations/directives for the shipping industry.
- Customers: Large companies that contract shipping services are increasingly demanding sustainable solutions for their supply chains, incentivising shipping companies to adopt greener practices.
- Port Authorities: Provide the infrastructure needed to support sustainable shipping, such as shore power, waste management facilities, and emissions control systems.

4.4 Criteria

In this section, first the outcome of the interviews is stated. These are input for the decision support tool. Afterwards, the weights of these criteria are given, which are also input.
The criteria are identified by interviewing the relevant internal stakeholders. These interviews are stated in full in appendix B. Since the research was done at the office of Jumbo Maritime, the managers of the different departments have been interviewed, which contain crucial knowledge about their departments and the company. These are the Operations Department, Technical Department, Commercial Department and the Sustainability Department. Also, DNV was interviewed as they are experts on the maritime sector. They are the marketleader when it comes to managing the data of maritime vessels (see appendix B.7).

4.4.1 Interview outcomes

There have been done numerous interviews as can be read in this section, however conversations also have been held with employees of Jumbo Maritime, like an purchaser. He buys in the bunker fuels for the vessels and when asked if he has ever bought biofuel, which is more expensive than other fuels, he stated the customers do not want to pay extra for being sustainable. However, he did also state that he has bought biofuel in the past but the reason for this was that the price of it was lower than MGO. So again, price made the decision. Next, the outcome of the different interviewees is stated. The interviews were aimed at finding out which criteria were deemed as relevant when deciding over which innovation to implement to decrease GHG emission of the vessels from their perspective.

From the **technical superintendent**, which is responsible for the operability of the vessels, it became clear in the interview, seen in B.1, that it is needed to know how a vessel will behave in certain conditions on certain routes with a certain load. With this data, a more reliable operational profile can be made and depending on this data, a suitable measure can be chosen. Also, based on this data, the Commerce can offer a job to a client based on this updated operational data. This leads to more reliable insights, less delays and less GHG emissions. Then, it also became obvious that it requires both new technologies and changes in how ships are operated to decrease the GHG emissions. Technical solutions focus on improving energy efficiency, while operational changes aim to manage ships in ways that lower emissions. The biggest challenges are cost, time, and adapting new technologies to older ships. High costs and uncertain ROI make it hard to justify expensive solutions. The maritime industry is cautious, and retrofitting older ships is complicated due to limited drydocking opportunities and differences in how ships are used.

From the **operational manager**, which is responsible for the day-to-day operations, it became clear from the interview, seen in B.2, that it is relevant for operations to be fast, safe and without damage. Next to this, it is also very important to be fuel-efficient in order for the costs to be low, due to fuel usage and emission certificates. Changes often require extra effort, such as monitoring the data, adjusting operations, and training crews to use new methods. While this can initially create resistance (and work), the long-term goal with reducing the GHG emission is inevitable. In the past, cost savings drove decisions like reducing speed, with lower fuel costs being the primary benefit. However, with new regulations such as FEUM and ETS coming into effect, reducing emissions has become a critical focus, which directly impacts costs. This is changing the way shipping companies balance their priorities: environmental goals are integrated with operational and commercial strategies.

From the **sustainability manager**, which falls directly beneath the CFO, it became clear from the interview (see B.3) that a clear plan is needed to align Jumbo Maritime's goals, the regulations, and customer demands in order to be future proof. But this roadmap is missing, with clear targets and deadlines thus being unknown. When deciding which measure to implement to decrease GHG emissions, the following criteria became visible: price, installation time, impact on procedures, energy-saving, TRL and regulations. The regulations are leading and price is the most important criteria, since this decides (just as TRL) whether the business case for the board of directors is positive. Other important factors include installation time, how changes affect the crew, and the potential to get subsidies. Lastly, reputation is becoming more important for clients and employees.

From the **commercial manager**, see B.5, who has been working here for the past 25 years, it became clear that the ROI is the most important because if the business case is positive, it will be taken seriously. Next to that, TRL is important, just as the operability with regard to free deck space. This is why he is not the biggest fan of WASP. Everything beneath the waterline though, does not impact the operation, and is thus easier to be successful. He also noted that it is important that it can be build in during dry dock since the market is very strong which leads to not wanting to spend time in drydock. He wants to be proactive towards understanding the future demand, such as anticipating transport needs for petrochemical and wind projects. Also it is very important to adhere to the evolving regulations while balancing cost efficiency. Further, sustainability efforts, like WASP, are seen to impact the company's reputation positively but it faces challenges in terms of customer willingness to pay extra. About the future, he expects that developments depend on the infrastructure and market dynamics which are shaped by larger industry players, like Maersk. Despite wanting to innovate, financial viability and ROI remain crucial in decision-making.

From the **technical manager**, see B.6, who is responsible for keeping the vessels safe and operational, the key criteria is maintaining operational, while staying reliable and being financial attactable for clients. Innovations must not interfere with the core operations, such as crane functionality or free deck space and it must align with the vessels operational profile. They should be realistic, avoiding significant structural changes that would require reclassification. Financially, innovations should offer a payback period of 3-5 years and manageable maintenance costs. Other considerations are TRL and alignment with sustainability goals to enhance reputation and meet client and regulatory expectations. What really misses at Jumbo Maritime, is a clear strategy towards becoming sustainable: a roadmap.

From **DNV**, see B.7, it became clear that the maritime sector has many opportunities to become more sustainable, but it also faces significant challenges. For any solution to work, it must match the specific vessels needs, such as its trade routes, how it operates, and when it is scheduled for maintenance. Digitalization is a major opportunity, as it helps with better planning, predicting maintenance, and saving fuel. However, there are big obstacles, like high costs for new technologies, limited availability of alternative fuels, and customers who focus mainly on price rather than sustainability. Regulations are currently the biggest driver for change. They push companies to either upgrade older vessels or replace them with new, more efficient ones. Without these rules, there would be less urgency to reduce emissions. To make progress, companies need a clear plan that lays out their goals and the steps to achieve them. This plan should be based on reliable data and tailored to their fleet. With the right strategy, the maritime sector can balance sustainability with financial and operational needs. Thus, when implementing a sustainable measure, it must match the vessel's operational profile, be cost-effective with a clear payback period (ROI), and comply with environmental regulations. They should be reliable, maintain operability, and fit into existing maintenance schedules to avoid downtime since time = money.

Criteria for evaluating measures that reduce GHG emission

Blow, the identified criteria from the interviews are listed and described.

- Return on Investment (ROI): Central to assessing the financial viability of an innovation. For instance, the WASP system is considered viable if it contributes to a significant amount of additional operational days and/or significant cost savings. ROI is also called payback period since it goes into how much years it takes to earn the investment back.
- Operational profile: The operational profile is important as it determines how an alternative is influenced by external factors such as wind, waves, and water temperature. These environmental conditions impact the effectiveness of certain technologies; for example, water temperature affects the efficiency of waste heat recovery (WHR) systems and the rate of marine growth on the hull. Additionally, vessel speed and operational patterns play a crucial role—Jumbo's vessels operate at lower speeds and remain stationary more frequently than container ships, which affects fuel consumption and technology performance. This criterion is specifically scoped to ocean-going HLVs, ensuring that selected measures align with their unique operational characteristics.
- Regulatory Compliance: Ensuring that ships comply with regulations like FEUM is a priority, especially given the financial implications of non-compliance. This is binding and not an option.
- Technology Readiness Level (TRL): Solutions need to be mature enough for integration, minimizing risks associated with new technology. **TRL has been replaced with CRI (Commercial Readiness Index), which is the basically the same as TRL but more advanced. In appendix A.11.5 this choice is explained further.**
- Installation Timing: Retrofitting or implementing innovations must align with routine drydocking to avoid costly downtime, reflecting the sector's urgency to maximize operational days. The installation will only occur into drydocking when the ship goes in for maintenance. When the installation takes longer than that, it must be a very good measure since again: extra downtime = ship can not be used = potential revenue lost.
- Operational flexibility: The vessel must be able to operate in the way it is supposed to operate. It must still perform key tasks like speed, crane use, and cargo handling after adding sustainability measures. If not, it can cause delays, which lowers efficiency, and disrupt operations which is bad for business.
- Safety: Non-negotiable in maritime operations, ensuring that innovations do not compromise the safety of personnel or cargo. Since it is non-negotiable, safety has not been used in the model. If a measure is unsafe, it will not even be an option. Safety has also been shown as a core principle within Jumbo Maritime by its Stay Well Program, as also explained in the SWAT analysis in section 1.5.

Classification criteria The selection of alternative measures is based on four classification criteria: safety, regulatory compliance, Technology Readiness Level (TRL) and maximum CAPEX.

- **Safety**: Safety is a non-negotiable constraint, and alternatives must meet a minimum threshold to be considered in the analysis. If an alternative does not fulfill safety requirements, it is deemed unviable. These constraints are derived from interviews with department managers and the board of directors. Safety is a key value within Jumbo Maritime, as reflected in the Stay Well program.
- **Regulatory compliance**: Compliance with environmental and maritime regulations is mandatory. Measures that fail to meet international regulatory standards (e.g., IMO regulations) are not considered viable alternatives. So, all alternatives must contribute to reducing GHG emissions, as non-compliance with regulations leads to financial penalties.
- **Technology Readiness Level (TRL)**: An alternative must reach at least TRL 8 to be included in the analysis, ensuring it is near full deployment. Additionally, the CRI is used to assess commercial readiness. Alternatives with a low TRL are not considered promising for Jumbo Maritime. The scale is shown in appendix A.11.5.
- **Maximum CAPEX**: Budget constraints limit capital expenditures to a maximum of 1 million EUR. Unlike industry giants such as Maersk or MSC, Jumbo Maritime has smaller budget constraints, making cost-effectiveness a critical factor in the selection process. This can be read in appendix B.

By applying these criteria, Jumbo Maritime ensures that selected innovations align with operational feasibility, regulatory requirements, and financial constraints.

4.5 Weights to criteria

Weighing the criteria, this is where the board of directors comes in. They are interviewed on what they think of the criteria and if satisfied, what the appropriate weights are. Here, the BWM is used for appointing these weights relative to the "best" and the "worst" criteria using pairwise comparison. Also see section 4.2.4 for an explanation about the MCDM.

4.5.1 Outcome interview board of directors

A structured interview has been done separately with the CEO, COO and CFO. This interview has not been transcribed since they simply gave numbers. The main aim of these interviews was to get weights to the identified criteria, which are described in section 4.4. Firstly, there was elaborated on this thesis project to get them accustomed with the subject. Next, the five criteria were clearly explained with examples. The two constraints safety and regulatory compliance are checked with the board of directors to see if they agree, and they completely did.
They all stated the same opinion: ROI is the most important. In fact, the rest of the criteria do get translated into the ROI, since the ROI is impacted by them. This is shown by the following reasoning: if the installation time is long, it costs money since the vessel can not be operated; if the operational profile doesn't match the alternative, it is less efficient, resulting in costing money; if operational flexibility gets compromised, the organization becomes less capable of completing tasks, leading to a reduction in revenue and profitability. When it was made clear that these criteria had to be seen separately in order to do the analysis, it was well understood and scores were given to the BWM.

More was being made clear in the interview. As seen in B.8, an innovation must be approved by the whole board if this is between 500 000 EUR and 1 million EUR. Above it, the Supervisory Board will join the decision, and below the COO is permitted to do it solely. He is advised in this process by the technical department and operations. Further, it was addressed that reputation is playing an increasingly important role within Jumbo Maritime, due to three reasons:

- Externally, to be attractable for (potential) clients and for the society.
- Regulatory compliance, reduce GHG emission otherwise penalties are received and this costs money.
- Being a attractable employer by taking its responsibility with becoming more sustainable. In the end, it is for the future generation, and they are attracted to companies who share the same values, as becoming sustainable is one of these big values.

The scores which were given by the board of directors, can be seen in appendix A.12. They were strongly similar, as depicted below in figure 26. Also, all their pairwise comparison consistency levels were acceptable, which indicates consistency in the input. Lastly, the scores of the boardmembers are averaged due to them making decisions together. These scores are given by conducting a structured interview in which they just had to give numbers. Getting these numbers is part of the BWM method and since just the numbers are asked, no transcription is made. In the end, this is input, given by the board of directors. In contrast, the process of achieving the criteria has been transcribed since this is part of the decision support tool and not raw input.

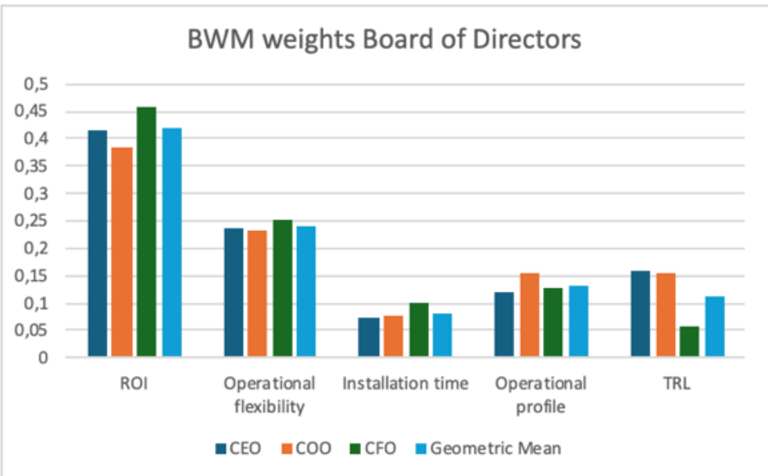

Figure 26: Weights of the criteria per Board of Direction member and average

4.6 Decision Support System

The decision support system (DSS) has multiple sources of input and is designed in a certain way. In this section, it is described how they work together and how the DSS finally works. In the end, it is all about transparency.

Firstly the **regulations**, which determines the playing field, coming purely from literature reviw. The regulations influence various aspects of the calculation process for determining the final ranking of the alternatives.

- Calculation of the reward factor of using WASP;
- Calculation of the ROI: ETS costs.

Then the **alternatives**, these comes from a literature review and Jumbo Maritime.

- They give input into the model in terms of which alternative is being used in the DSS;
- How much a certain alternative saves fuel, appendix A.14;
- Calculation of the ROI: CAPEX & OPEX
- Which score the alternative gets on the criteria: "Operational flexibility", "Installation time", "Operational profile" and "CRI". This is written in the so-called **performance matrix**. These scores are explained in appendices A.11.2, A.11.4, A.11.3

Next, the alternatives are ranked based on different **criteria**. These criteria, and their weights, are thus crucial in evaluating the different alternatives. And lastly, the initial input in the model comes from a **case-study**. The case-study in this thesis is conducted on the HLV Fairmaster.

4.6.1 Calculation

First, the parts which make up the ROI are calculated.

- Starting with the **fuel-savings per alternative**, this is calculated by multiplying the fuel-saving percentage (table 7) with the sailing days per year (case-study) with the amounts of fuel used per year (case-study). The amount of fuel per year is calculated by the price per metric ton of a specific fuel multiplied with the amount of that specific fuel. This is done for every fuel type separately and summed up to get the total fuel-saving in EUR/year.

  *Fuel-saving percentage per alternative (%) * Sailingdays per year (days) * (VLSFO (mt/day) * VLSFO-price (EUR/mt) + MGO (mt/day) * MGO-price (EUR/mt) + biofuel (mt/day) * biofuel-price (EUR/mt)) = Fuel-savings per alternative (EUR/year)*

Alternative	Fuel-saving % (per metric ton fuel)
WASP	4.00
Wavefoil	4.50
ALS	5.00
Hull cleaning	6.00
Flipper Zipper	1.50
Propeller Boss Cap Fins	4.00
Eco-control	3.00
Heat recovery	5.00

Table 7: Fuel-saving input percentages of different alternatives.

- Then the **ETS-savings**. This is built up by multiplying the amount a vessel spends in the EU (case-study), since ETS only is applicable when sailing in EU waters, with the price per ETS allowance with the amount of sailingdays per year with the amount of fuel that a vessel saves when using a specific alternative (table 7). This number is the savings of a vessel per year when emitting a total of 1 ton of CO_2 when using that specific alternative. Due to different fuels are used, this number is multiplied with the amount of a specific fuel used and its respective CO_2 equivalence value (depicted in appendix A.11.1, figure 30). This must happen since VLSFO, MGO and biofuel emit different amounts of CO2 per metric ton.

*EU-time (%) * ETS-price (EUR) * Sailingdays per year (days) * Fuel-saving percentage per alternative (%) * (VLSFO (mt/day) * CO2eq-VLSFO (mt) + MGO (mt/day) * CO2eq-MGO (mt) + biofuel (mt/day) * CO2eq-biofuel (mt)) = ETS-savings (EUR/year)*

- Also the **FEUM penalty savings** must be calculated for the WASP, since this is a major reason why the WASP can be chosen. The formulas for this is derived from the official European Union FEUM regulation document (European-Parliament, 2023). These are depicted in appendix A.13.

- Next, the **ROI** can be calculated by dividing the investment cost (CAPEX) with the continuous costs (OPEX + Fuel-saving per year + ETS savings + FEUM penalty savings). This gives the duration until the ROI becomes positive which is crucial information for a company, as seen by the weight it also got from the board of directors (section 4.5). The bigger the ROI, the longer it takes until the investment pays off. Also, since the future is unsure, a longer ROI might be even worse than initially thought, for example: if the regulations change in 5 years which leads to the removal of the FEUM reward factor, than the ROI is not reliable anymore if that ROI is bigger than 5 years.

When the ROI is known, the performance matrix is filled. Now the scores of the different criteria have to be standardized. This makes the scores in every column between 1 and 10, which results in a final score between the 1 and 10 (which is perfect for comparing). These standardized scores are then multiplied with the weights (which come from the board of directors) and adding these all up, makes the final score per alternative.

5 Results

In this chapter, the results from the Decision Support System (DSS) are shown. Starting off with the criteria, followed by the performance matrix, then the final ranking of the alternatives with the current input which stems from a case-study on the HLV Fairmaster. In addition, results from the sensitivity analysis, verification tests and MACC are presented.

5.1 Criteria

The criteria became clear from the interviews. This outcome is described in section 4.4. Below, in table 8, the outcome is shown.

Interviewee	Criteria
Technical superintendent	Cost (OPEX, CAPEX, and ROI), installation time, TRL, operational profile.
Operational manager	Fast, impact on procedures, safe, costs (fuel and ETS).
Sustainability manager	Price, installation time, impact on procedures, energy-saving, TRL, and regulations.
Commercial manager	ROI, operational flexibility, safe, TRL
Technical manager	Safe, operational flexibility, ROI, TRL
DNV	Operational profile, ROI, regulations, operational flexibility, TRL
Summarized	**ROI, TRL, operational flexibility, safe, regulatory compliance, installation time, operational profile**

Table 8: Criteria as identified by different departments

Note: Alternatives had to pass a threshold (TRL > 8) to be included in the analysis, thus TRL became a classification criterion. After this, the CRI was used to assess differences in readiness and thus became the criterion that was used in the DSS.

Weights

The weights are also known, as can be read in section 4.5. From the structured interviews with the board of directors, the following scores became evident.

Best to Others	ROI	Operational flexibility	Installation time	Operational profile	TRL
ROI	1	2	5	4	3

Table 9: Best main criterion compared to others by CEO of Jumbo Maritime

Best to Others	ROI	Operational flexibility	Installation time	Operational profile	TRL
ROI	1	2	5	3	3

Table 10: Best main criterion compared to others by COO of Jumbo Maritime

Best to Others	ROI	Operational flexibility	Installation time	Operational profile	TRL
ROI	1	2	5	4	7

Table 11: Best main criterion compared to others by CFO of Jumbo Maritime

The tables 9, 10 and 11 show that the board of directors considers the ROI to be the most important. Operational flexibility scores very close to this best criterion, which shown consensus over the three boardmembers, even though they were interviewed separately. Overall, the scores are very similar. Installation time, Operational profile and TRL score lower but this differs in how they are valued. The CEO and COO are the most similar, providing an almost identical comparison. TRL scores the second best, than the Operational profile, following with the installation time. The COO considers the Operational profile to be as important as the TRL when comparing the ROI to these criteria.// The CFO however, considers the TRL to be clearly the least important criterion, when comparing this to the ROI. The Operational profile and installation time are consistent with the other boardmembers.

Others to the Worst	Installation time
ROI	5
Operational flexibility	4
Installation time	1
Operational profile	2
TRL	3

Table 12: Others compared to worst main criterion by CEO of Jumbo Maritime

Others to the Worst	Installation time
ROI	4
Operational flexibility	4
Installation time	1
Operational profile	3
TRL	3

Table 13: Others compared to worst main criterion by COO of Jumbo Maritime

Others to the Worst	TRL
ROI	7
Operational flexibility	5
Installation time	2
Operational profile	3
TRL	1

Table 14: Others compared to worst main criterion by CFO of Jumbo Maritime

Tables 12, 13, and 14 show how the board of directors rate the criteria compared to the worst criterion. The worst criterion differs between the different board members, as also can be seen from the Best-to-others comparison. The CEO and COO have chosen the installation time to be the worst criterion and the CFO the TRL. But the severity in which they rate the differences, is again very similar. The CFO is more distinct in the comparison with giving a 7 on how much the ROI is more important than the worst criterion, which is the TRL.

	CEO	COO	CFO
Input-Based CR	0.20	0.20	0.12
Associated Threshold	0.23	0.23	0.28

Table 15: Table showing input-based CR and associated threshold values.

In table 15, the input-based consistency ratio (CR) and its associated threshold value are shown. Since the CR is lower than the associated threshold, the answers of all board members are consistent.

The outcome of the weights is shown visually below in table 27. These are calculated by taking the geometric mean of the weights of the board members' criteria separately. The weights show that the ROI is by far the most important criteria, followed by Operational flexibility. Next, Operational profile, CRI and lastly, Installation time.

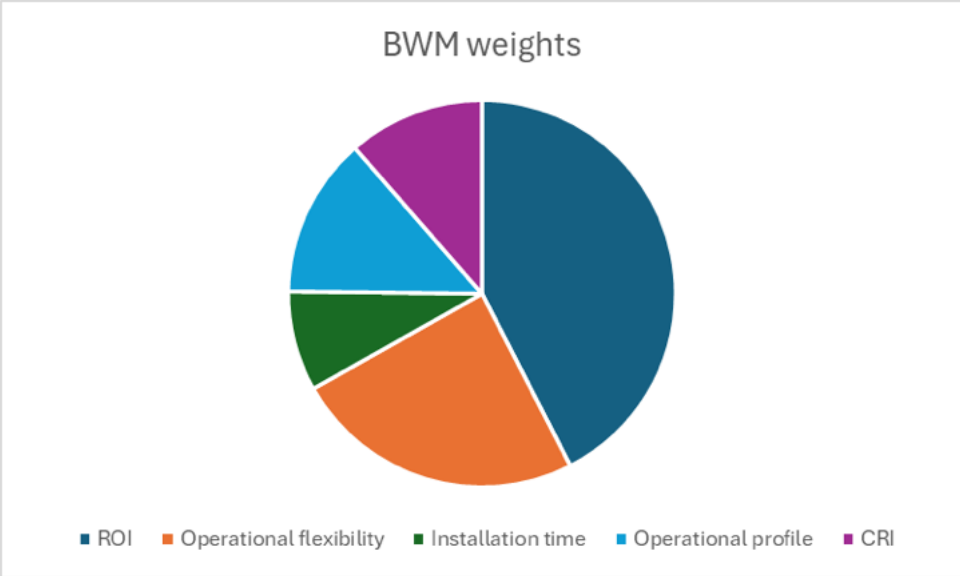

Figure 27: BWM weights

5.2 Matrices

First, the outcome of the FEUM savings calculations are presented, which is input for the ROI matrix. Then, the full ROI matrix, followed by the performance matrix. This section concludes with the results of the total DSS.

5.2.1 FEUM savings

The outcome of the FEUM calculations is shown in table 16. It can be seen that over half of the penalty is reduced due to the WASP in the calculated base-case (case-study on HLV Fairmaster) of 94.12 grams CO2-eq/MJ, compared to an actual GHG intensity of 110 grams CO2-eq/MJ.

Penalty FEUM (EUR)	**Actual GHG intensity: 94,12**	**Actual GHG intensity: 110**
Total penalty without WASP	**€ 331.780,62**	**€ 1.225.501,94**
Total penalty with WASP	**€ 140.270,93**	**€ 1.061.633,12**
Money saved due to WASP	**€ 191.509,69**	**€ 163.868,82**

Table 16: Penalty and savings under FEUM for different GHG intensities.

5.2.2 ROI matrix

The calculations, as shown in section 4.6, result in a filled ROI matrix. This has been placed in figure 28. Note, the values are relative to the current situation, in which no measure is implemented. Negative values are costs and positive values are savings. The ROI is the number of years needed to pay back the investment. Also, the values are measured in thousands of EUR.

	CAPEX	OPEX	Fuel saving	ETS savings	Fuel EU	Subsidy	
Alternative	*EUR*	*EUR/year*	*EUR/year*	*EUR/year*	*Applicable*	*Applicable*	ROI (years)
WASP	-750	-15	126	34	Yes	Yes	**2,33**
Wavefoil	-750	-35	139	38	No	No	**5,30**
Air lubrication	-950	-15	126	34	No	No	**6,53**
Hull cleaning	-35	-105	151	41	No	No	**0,40**
Flipper Zipper	-30	-5	50	14	No	No	**0,51**
Propeller Boss Cap Fins	-125	-5	101	27	No	No	**1,01**
Eco-control	-100	0	76	21	No	No	**1,04**
Heat recovery	-400	0	151	41	No	Yes	**2,08**

Figure 28: ROI matrix

5.2.3 Performance matrix

This leads to a filled performance matrix, displayed in figure 61. The detailed scoring of each alternative on the remaining criteria is provided in appendix A.11. The performance matrix is standardized in order to give a final score between 1 and 10, this standardized matrix is displayed in appendix A.17.

	C1	C2	C3	C4	C5
	ROI	**Operational flexibility**	**Installation time**	**Operational profile**	**CRI**
Alternative	*Years*	*Scale 1-10 (#)*	*Days (#)*	*Scale 1-10 (#)*	*Scale 1-6 (#)*
WASP	2,33	9	15	5	4
Wavefoil	5,30	8	21	5	2
Air lubrication	6,53	9	14	7	2
Hull cleaning	0,40	9	1	10	4
Flipper Zipper	0,51	4	1	10	2
Propeller Boss Cap Fins	1,01	10	1	9	5
Eco-control	1,04	8	2	8	3
Heat recovery	2,08	9	21	7	5

Figure 29: Performance matrix (unstandardized)

5.3 Output of DSS

The performance matrix multiplied with the weights, seen in table 24, gives the final ranking, seen in 17 and seen in a cumulative chart in figure 30. It shows that ROI makes up for a significant part of the final score of a measure. hull cleaning and PBCF are constantly ranking high and Wavefoil and ALS constantly low. The remaining alternatives are in between.

Alternative	Total score
WASP	6,3
Wavefoil	3,2
ALS	3,5
Hull cleaning	9,2
Flipper Zipper	6,6
Propeller Boss Cap Fins	9,2
Eco-control	7,6
Heat recovery	7,0

Table 17: Alternative total score analysis

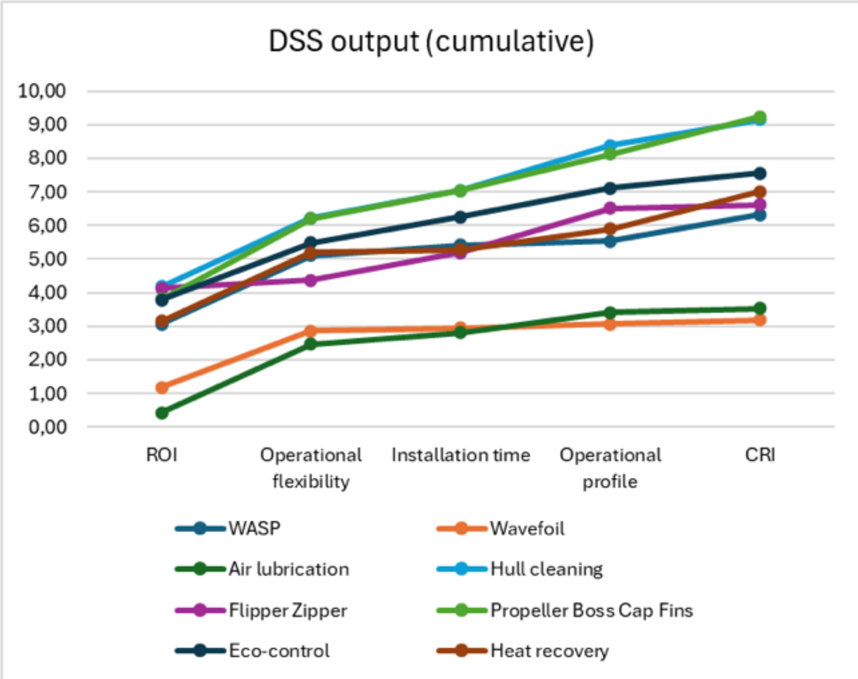

Figure 30: DSS output (cumulatively) across the criteria

5.4 Verification

Multiple verification tests have been done, which are all shown in appendix A.19. In these, the inputs are changed by using extreme values.

- VLSFO & MGO & Biofuel = 0 mt/day
  No fuel consumption shows to lead to no ROI differing score across the alternatives. The ROI is equal to the weight ROI has, which is 0,42. The final score is based on the four other criteria. This results in PBCF as best, and Wavefoil as the least promising option, as seen in 31.

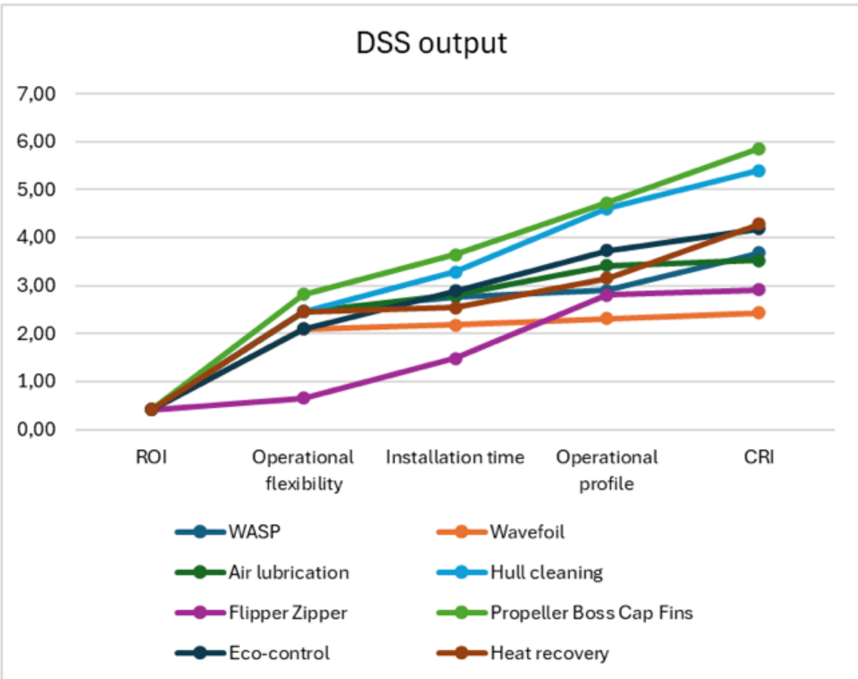

Figure 31: Verification: no fuel usage

- VLSFO = 1000 mt/day, MGO & Biofuel = 0 mt/day
  This shows to result in a very big FEUM penalty while the final ranking did not change, as seen in 18.

Alternative	Total score
WASP	6,2
Wavefoil	3,5
ALS	3,5
Hull cleaning	9,2
Flipper Zipper	6,5
Propeller Boss Cap Fins	9,1
Eco-control	7,4
Heat recovery	6,8

Penalty FEUM (EUR)	VLSFO & MGO & Biofuel combined
Total penalty without WASP	**€ 14.992.905,79**
Total penalty with WASP	**€ 7.480.726,88**
Money saved due to WASP	**€ 7.512.178,91**

Table 18: Alternative scores and FEUM penalty when VLSFO = 1000 and MGO & Biofuel = 0 mt/day

- Only the use of biofuel resulted in no FEUM penalty, leading to a lower score of WASP.
- If 0% of the sailing time is in the EU, the FEUM penalty equals zero.
- If 100% of the sailing time is in the EU, the FEUM penalty linearly increases with EU sailing time, as seen in 32.

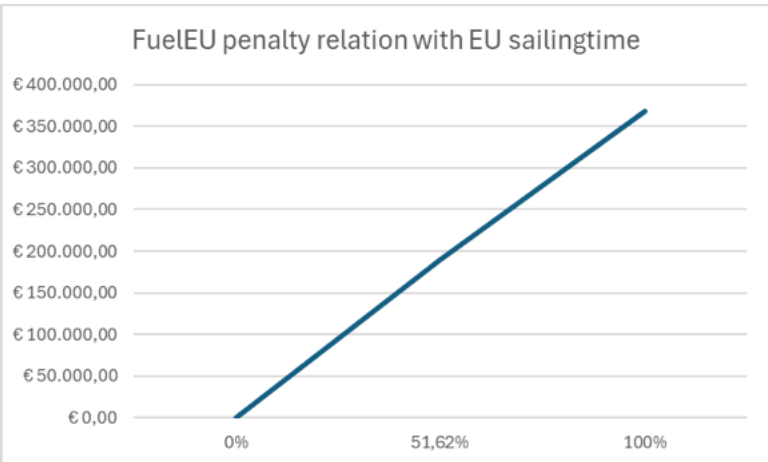

Figure 32: FEUM penalty relation with EU sailing time

- If sailing days was set on 0, it gave an error on every output.
- If hull cleaning was set on 10 (or any value above 4), the output did not change.

5.5 Sensitivity analysis

To check whether the final ranking is robust under different inputs, a sensitivity analysis is conducted on the DSS. This is done on the main input of the DSS which comes from the case study on the HLV Fairmaster, then on the ROI values and lastly on the weights. A sensitivity analysis helps decision-makers identify which solutions align best with their priorities and strategic goals, making sure that the selected alternatives remain effective and reliable in practice. Initially the sensitivity analysis was done with +/- 15%. Since this did not change the ultimate ranking significantly, it was deemed unnecessary to do it with +/- 10% and 5% as well. In the end, this section is about efficient reporting interesting findings from the sensitivity analysis.

5.5.1 Sensitivity analysis - Main input

The input values can be seen in appendix A.15. Every input changed with +/- 15%, except for the WASP reward factor and the hull cleaning times per year. The reason for this is that these are discrete values which can also have certain values. The rest of the initial input is continuous. The output of the sensitivity analysis on the main input, is placed in appendix A.18.1

Hull cleaning
You can't do 4,20 cleaning times per year for example. The ideal amount of hull cleaning times per year was set on 4. When choosing this alternative, it makes no sense to do it more than 4 times a year since there will not be additional benefit with regard to fuel-saving etc. However, to test the DSS, this test has been done with 6 times a year and the outcome did not change. With regard to the sensitivity analysis, input was changed to 0 and 2 times a year. The DSS was designed in a specific way in which it uses the highest and lowest scoring alternative to calculate the standardized values. This made changing the hull cleaning times a year having an effect on the ranking. 0 cleaning times a year, made the ROI 0. This resulted in hull cleaning getting the last place in the ranking, since ROI is the heaviest weight in the analysis. The rest of the alternatives stayed in the same ranking, as seen in figure 33.

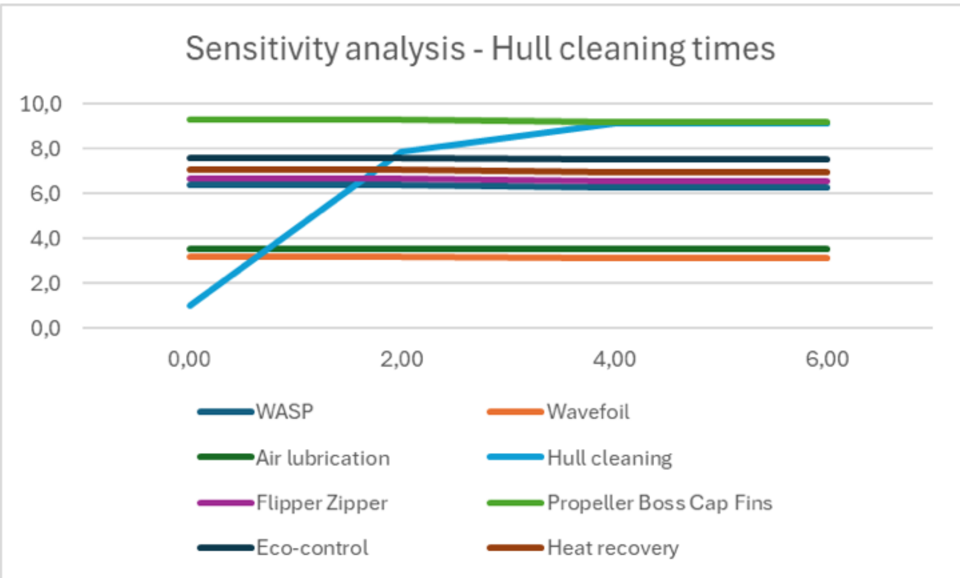

Figure 33: Sensitivity analysis of amount of hull cleaning times

WASP
The values of WASP were also changed. Since it gives no additional information if +/-15% is done, 1% and 5% were used as input to compare to the base-case of 3%. Plus, the WASP reward factor can not have different values outside of 1-5% as defined in the regulation, as can be seen in appendix A.13 in figure 57 and in appendix 19. This sensitivity analysis resulted in a difference of 1,2 point between the 1% and 5% case, as shown in table 19. However, the ranking did only differ in the case of 5% case with one place: WASP surpassed the Flipper Zipper with 0,1 point.
Also a separate case was examined: the scenario where the amount of hull cleaning was 0 and the WASP return factor was 5%. This is to see whether the DSS functions as it is supposed to: hull cleaning has to come out last.

WASP reward factor	1%	3% (Base-case)	5%	5% (0x Hull cleaning)
WASP	5,5	6,3	6,7	6,8
Wavefoil	3,2	3,2	3,2	3,2
ALS	3,5	3,5	3,5	3,5
Hull cleaning	9,2	9,2	9,2	1,0
Flipper Zipper	6,6	6,6	6,6	6,7
Propeller Boss Cap Fins	9,2	9,2	9,2	9,3
Eco-control	7,6	7,6	7,6	7,6
Heat recovery	7,0	7,0	7,0	7,1

Table 19: Performance of different technologies under varying WASP reward factors and hull cleaning scenarios.

Remaining variables
The final ranking of the other variables, which were changed separately in the sensitivity analyses, stayed the same. The only ones that changed were the hull cleaning times a year and the WASP as explained.

5.5.2 Sensitivity analysis - ROI

Table 20 shows the outcome of the sensitivity analysis on the ROI. In this figure, every alternatives outcome from the sensitivity analysis is shown. Note, this does not depict the ranking, it just shows the difference between the different cases of +/- 25% and the base-case of the alternatives separately. In appendix A.18.2, the rankings of every separate analysis can be seen with the changed ROI. Sensitivity analysis is usually done with 15% difference, but here it is done with 25% difference. The reason for this is that the ROI has a bigger probability of being different than the other variables because for some alternatives, like the Wavefoil, the CAPEX/OPEX is an estimation.

Alternatives	-25%	Base-case	+25%	Difference
WASP	6,67	6,33	5,99	0,68
Wavefoil	4,00	3,18	2,43	1,57
ALS	3,83	3,52	3,52	0,31
Hull cleaning	9,16	9,16	9,16	0,00
Flipper Zipper	6,69	6,62	6,54	0,14
Propeller Boss Cap Fins	9,40	9,24	9,09	0,31
Eco-control	7,72	7,56	7,40	0,32
Heat recovery	7,33	7,01	6,69	0,64

Table 20: Sensitivity analysis - ROI

5.5.3 Sensitivity analysis - BWM weights

The weights were also adjusted as part of the sensitivity analysis, shown in appendix A.18.3.
This demonstrates how changes in the perceived importance of certain criteria can influence rankings, particularly for alternatives that are more specialized or context-dependent. In the calculation of this, the weights were recalculated since the weights sum up to 1.0 in order to let the final ranking be between 1 and 10. This is needed because two analysis's can only be compared if their scale is the same. This recalculation was done by decreasing or increasing the weights with 15% and then rescale the remaining weights appropriately that they have the same value to each other relatively.

In table 54, it is shown how the output differs if the ROI is changed with 15% compared to the base-case. The Flipper Zipper has the biggest changes with almost 0,7 difference between the positive and the negative case. Wavefoil has the the least difference with 0,09 difference between the two scenarios.

ROI	-15%	Base-case	+15%
WASP	6,31	6,33	6,51
Wavefoil	3,28	3,18	3,19
ALS	3,88	3,52	3,32
Hull cleaning	9,21	9,16	9,36
Flipper Zipper	6,34	6,62	7,02
Propeller Boss Cap Fins	9,41	9,24	9,35
Eco-control	7,50	7,56	7,80
Heat recovery	7,06	7,01	7,15

Table 21: ROI sensitivity analysis

5.5.4 Sensitivity analysis - Fuel-saving percentages

The fuel-saving percentages are also adjusted to test how they influence the output of the DSS. This has not been done with the standard 15%, but the percentages are changed between an absolute 1 and 3% above and below the base-case. The amount of changing depends on the original percentage: if it is 5% in the base-case, 2% above and below is taken; if it is 2% in the base-case, 1% above and below is taken; except in the case of the hull-cleaning, since 3% would lead to a very interesting output, as is explained in the discussion in 6.2.4 and shown in table 22. 15% would not have a significant effect, since the percentages are already low: between 1 and 5,5%. Also, the values are estimated, based on literature (explained in section 6.3.3) but these are considerably sensitive to the actual vessel characteristics and its trip characteristics. This is why these percentages are changed more than in the other sensitivity analysis'. The output of every changed fuel-saving percentage, is shown in appendix A.18.4.

Also, the output of ALS is shown with the changed fuel-saving percentages is shown in table 23. It is seen that the scoring of the Wavefoil changes substantially due to a changed percentage of ALS. This leads to a changed ranking in the bottom two. The rest of the ranking stays consistent.

In figure 34, the changes of each alternatives can be seen in the low-, base-, and high cases of the changed fuel percentages.

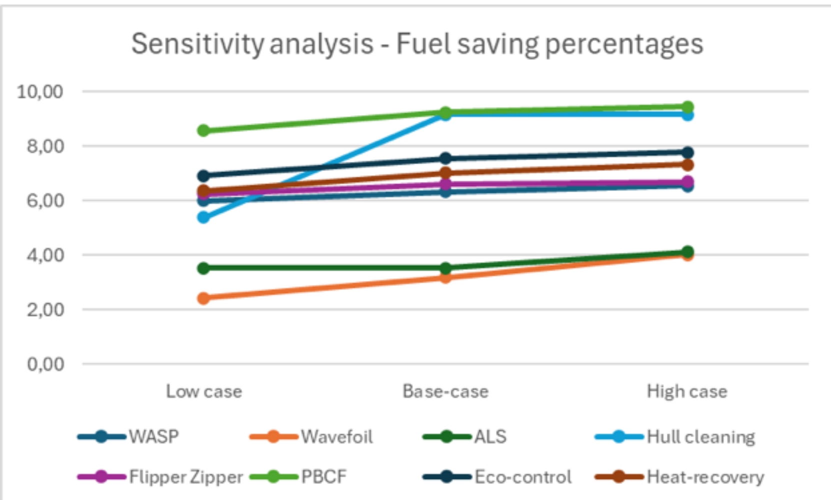

Figure 34: Sensitivity fuel percentages of alternatives

Hull cleaning	3%	Base-case (6%)	8%
WASP	6,16	6,33	6,26
Wavefoil	3,14	3,18	3,16
ALS	3,52	3,52	3,52
Hull cleaning	5,39	9,16	9,16
Flipper Zipper	6,39	6,62	6,52
Propeller Boss Cap Fins	9,03	9,24	9,15
Eco-control	7,35	7,56	7,47
Heat recovery	6,84	7,01	6,94

Table 22: Sensitivity analysis on fuel-savings percentage of hull cleaning

ALS	3%	Base-case (5%)	7%
WASP	6,84	6,33	6,04
Wavefoil	4,56	3,18	2,43
ALS	3,52	3,52	4,12
Hull cleaning	9,16	9,16	9,16
Flipper Zipper	6,65	6,62	6,60
Propeller Boss Cap Fins	9,42	9,24	9,15
Eco-control	7,74	7,56	7,46
Heat recovery	7,48	7,01	6,75

Table 23: Sensitivity analysis on fuel-savings percentage of ALS

5.6 MACC

A discount rate of 5% is used in the Marginal Abatement Cost Curve (MACC). It balances the value of upfront costs and long-term savings fairly, which makes it suitable for measures like the WASP or PCBF which have a high lifetime. An article from Young (2021) discusses appropriate discount rates for climate-related projects, and concludes that rates around 5% are often suitable for balancing immediate expenditures with long-term environmental benefits. The MACC is shown in figure 35 and the values on which this curve has been made, are shown in table 72.
In the MACC, it can be seen that Eco-control has the highest cost-effectivity since it has the largest savings per ton of CO2-eq. Hull cleaning has the lowest, since it has the lowest savings per ton of CO2-eq that is saved. Since all the measures are below the x-axis, this shows that all the alternatives are cost-efficient by having a negative cost per reduced ton of CO2-eq per year. This is the goal of the MACC, to see how the measures score on their potential of reducing a ton of CO2-eq. How lower or higher it gets on the y-axis, how larger the (negative) cost per ton of CO2-eq. Also, WASP has the biggest potential of reducing GHG emission and the Flipper Zipper has the least. This can be seen by the size of the area on the x-axis. The area (x * y) represents the total cost (or savings) of the measure. This potential is the biggest at the WASP as well.

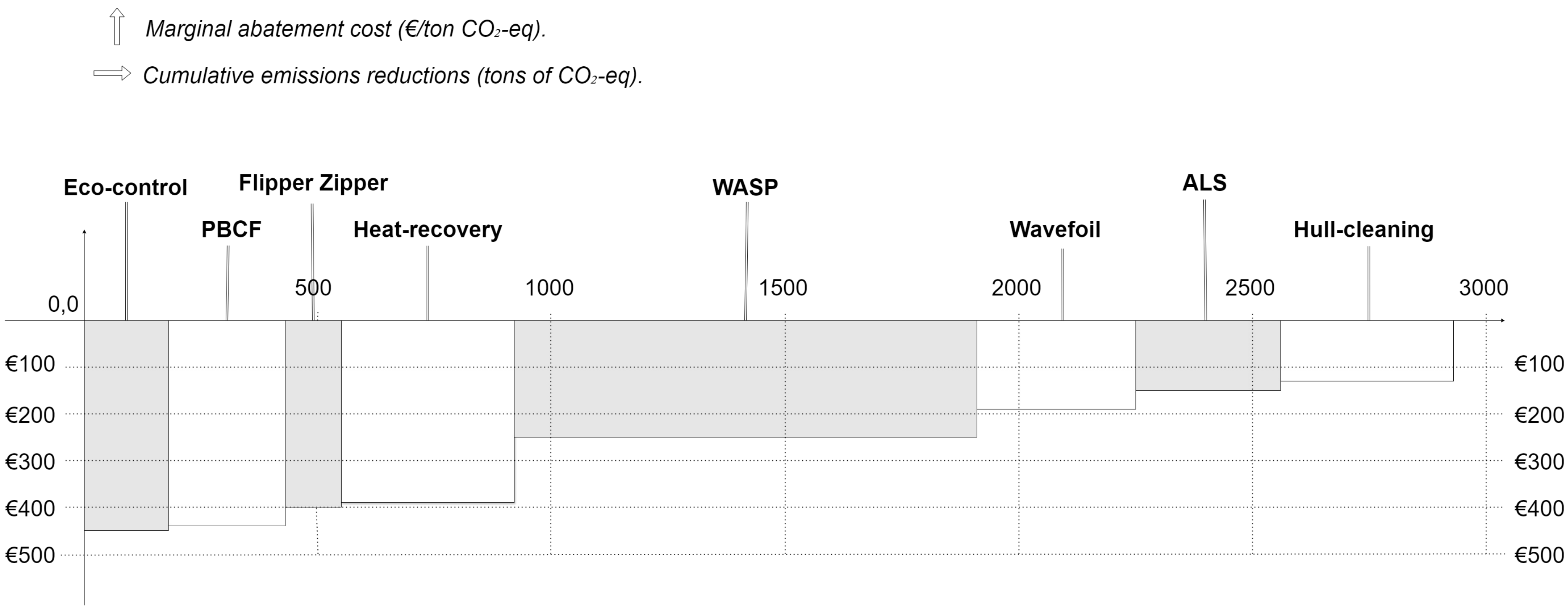

Figure 35: Marginal Cost Abatement Curve

6 Discussion

In this section, behavioral considerations and results are discussed, providing a well-balanced reflection on expert insights, findings and limitations.

6.1 Behavioral considerations

People might have a bias for a specific alternative. When a tool is transparent, like this one, it works preventative against biases. Since input can always be changed, the tool might give different outputs to different values but if the tool is rightly structured, biases are brought down to a minimum.

There can be two general biases in decision-making: cognitive biases and motivational biases. Cognitive biases can be summarized as “faulty mental processes that lead judgments and decisions to violate commonly accepted normative principles". Motivational biases are "conscious or subconscious distortions of judgments and decisions due to self-interest, social pressures, or organizational context.” (Rezaei, 2023). They differ in the fact that cognitive biases are, in contrast to motivational biases, specifically against accepted principles and not necessarily out of self-interest. For example, this happens with availability bias, where events that are easier to remember seem more likely than they really are.

During the process of writing this thesis, it is possible that several biases might have influenced the outcome, which are listed below. For the sake of being complete and transparent, these have been listed. However, further research has to confirm whether this has played a part.

Cognitive biases

- Equalizing bias
  This means that the board of directors would give similar weights to all criteria. However, this might have been prevented with the choice for the BWM as MCDM. This can be read in section 4.2.4. In summary, the process of the BWM makes the decision-maker give a score to the best-to-others criteria and the others-to-worst criteria. In this way, separate choices could have been made for the same trade-off, which shows (in)consistency of his answers.

- Overconfidence bias
  This can happen when the board of directors provided estimates for the weights of the BWM weights. These scores are depicted in appendix A.12. This bias means that a given parameter might get a score that is above the actual performance (overestimation).

- Omission of important variables
  The bias occurs when an important variable is overlooked, as in interviews with managers and external parties. These interviews are depicted in B. Since multiple parties are interviewed and similar responses were derived from these interviews, the chance that an important variable is overlooked is minimized.

Motivational biases

- Confirmation bias
  The bias occurs when there is a desire to confirm one’s belief, leading to unconscious selectivity in the acquisition and use of evidence. This is seen at Jumbo Maritime in the choice between different alternatives. The WASP has been prone to this bias to people investing a lot of time in them. They get attached and this might even lead to affect influenced bias, which occurs when there is an emotional predisposition for a specific outcome or option that faults judgments. The confirmation bias frequently occurs in general when presenting the results of implemented measures: the positive aspects get highlighted, like the amount of GHG reduction; and the negative aspects get placed to the background, like the height of the initial cost or placement issues.

- Optimism bias
  When the different alternatives are reviewed, it happens frequently that the outcomes overestimates positive outcomes that aligns with one’s hopes or expectations. This then connects to the confirmation bias because when someone has formed an optimistic expectation, they might actively seek out information that supports this positive outlook while disregarding evidence that contradicts it. For instance, an individual might focus on data that reinforces their belief in a project’s success, ignoring potential challenges or risks highlighted in other data.

However, these motivational biases can largely be prevented by using specific data. These are hard numbers and specified per GHG-decreasing measure:

- CAPEX;
- OPEX;
- Fuel-saving percentage;
- Other input, as depicted in appendix A.15.

6.1.1 Bias in this thesis

However, it is important to note that biases may still be present when using hard numbers as input. Relying on data from the manufacturer of a specific alternative carries the risk of confirmation bias, which is further discussed in the limitations (section 6.3).

To assess the value of the DSS, it was presented to the manager of the Technical Department, as he is the main initiator of GHG reduction measures and has a strong sense of what is feasible. He stated that he fully agrees with the structure of the DSS and finds it highly understandable. He also noted that its reliability can be tested by adjusting the percentage of time a vessel operates within the EU and observing the impact on the WASP. Since WASP is most affected due to the FEUM, as seen in the sensitivity analysis on EU sailing time, which is shown in table 36 (based on appendix A.18.1, table 37), this confirms this effect. This indicates that the DSS functions as intended. However, he did not fully agree with the input. When it was clarified that the focus of this thesis is on the DSS structure rather than the input itself, he was satisfied.

This again shows that the WASP has been a major topic in Jumbo Maritime, which might also point to a certain preference towards this alternative. So, it is a good sign that it is accepted that this alternative did not became one of the best alternatives. This is also shown by the concluding statement of the manager of the Technical Department on agreeing with the DSS's output, demonstrating that transparency helps in accepting the results and preventing biases. Further, to make sure the DSS is fair and objective, (changed) input must be managed and checked for biases. The same applies to the output: it must be interpreted and reported objectively to prevent results from being presented in favor of a specific alternative.

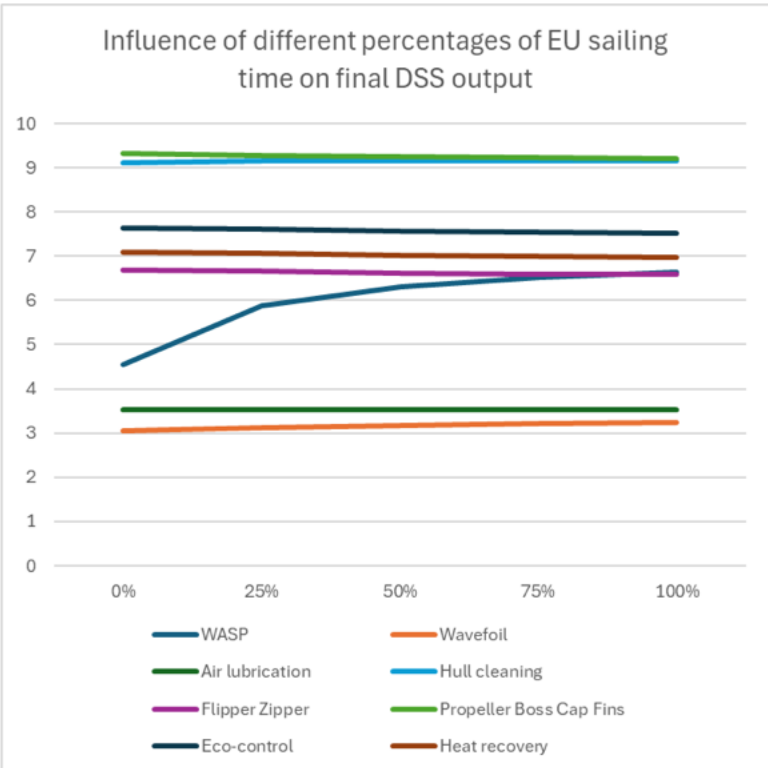

Figure 36: Influence of different percentages of EU sailing time on final DSS output

6.1.2 Planning fallacy and strategy

The planning fallacy has also been noticed within the company. The planning fallacy arises when individuals tend to underestimate the time, cost, and risks that are associated with future actions and overestimate the benefits of positive outcomes. This has been seen with the implementation of the WASP. The WASP has been leased from Econowind and now they are looking into buying them for permanent use. This will be done but the idea from the WASP comes ultimately from initiatives. Within the technical department, the idea arised and then there was made a business case on the WASP. This business case was reviewed in isolation to other measures that decrease GHG emission. The high initial cost is leading in this initiative: that is why they were leased as a trial. When carefully evaluating the WASP in comparison to other measures, for which the DSS can be used, a comparison can be made with how "good" the initiative is. There do exist low hanging fruits which might be better than WASP, like the PBCF. However, this decision depends on several factors, like what is the strategy of the company. If the strategy is to decrease the penalty cost due to FEUM, then the WASP is perfect. But if the aim is to decrease GHG emission as cost-efficient as possible, then Heat-recovery seems like the better choice. So, the strategy is leading: how much GHG emission has to be reduced with which budget? This is where a MACC (section 5.6) comes in handy.

6.1.3 Transparency

Transparency in the development of the DSS is essential for ensuring accuracy, reliability, and trust in the outcomes it produces. This is also exactly the reason why EXCEL has been chosen to use for the generation of the DSS: it is no black box. It is very clear what is used, where and why. Being transparent means clearly documenting the assumptions, methodologies and data sources that are used. This allows others to replicate the research and get similar output. This allows others also to understand the rationale behind its design and outputs. This openness is crucial for identifying, preventing and mitigating biases that otherwise might compromise the model. For example, without transparency, optimism bias could lead to the inclusion of favorable assumptions, changing the results. Similarly, confirmation bias could influence the selection of variables or parameters that align with pre-existing expectations, rather than representing an objective reality. So how data is selected, processed, and interpreted, must be sound and clear. By making the structure of the DSS transparent, it is all clear for the reader why and how it is done in the specific way. This approach helps to prevent the DSS being a black box by ensuring diverse perspectives are considered and preventing subjective biases from being incorporated in the model.
Transparency also promotes accountability because stakeholders and other users can track decisions made during the modeling process and why those are made. And ultimately, a transparent development of the DSS makes that stakeholders can trust the output, making it a trustworthy and unbiased support for effective decision-making.

6.2 Discussion of results

This section discusses the results. First the BWM weights, then the FEUM calculation and then the ROI.

6.2.1 BWM

BWM was chosen as the MCDM method to determine the weights, based on structured interviews with the board members. The criteria used were identified through semi-structured interviews with the relevant department managers.
During the structured interviews, board members were asked to rate the Best-to-Others and Others-to-Worst using a Likert scale from 1 to 9. This approach minimized discussion and reduced the workload for the board members, as they only needed to focus on the five criteria and their relative importance, rather than debating individual scores. This lower cognitive load made the process more comfortable for decision-makers and could lead to more accurate and consistent scoring.
However, a potential downside is that board members might have valuable insights into why they make certain decisions, but the methodology was not designed to capture this. Instead, the goal was to let department managers define what is important, while board members determine how much weight each criterion should carry. In the end, the board makes the final decisions and this approach makes sure that the priorities, set by the department managers, aligns with the way the board values them.
The individual weights from the board members show strong alignment, with very similar scores, as can be seen in table 24. This indicates that the board has clear priorities when deciding which measure to implement. ROI (costs) is by far the most important factor, carrying a weight of 42%. Next is operational flexibility, ensuring that the vessel can perform as designed. Operational profile follows, as the measure needs to match

the vessel's routing, weather conditions, and operational needs. CRI is ranked lower, which makes sense since all alternatives already meet a minimum threshold (TRL). This is also why TRL was set as a classification criterion rather than a weighted factor. Installation time is the least important, as installations happen during scheduled docking. However, shorter installation times are still preferred to avoid extending the original docking plan.

Criterion	CEO	COO	CFO	Geometric mean
ROI	0.42	0.38	0.46	0.42
Operational flexibility	0.24	0.23	0.25	0.24
Installation time	0.07	0.08	0.10	0.08
Operational profile	0.12	0.15	0.13	0.13
CRI	0.16	0.15	0.06	0.11

Table 24: Weights assigned by CEO, COO, CFO and geometric mean

6.2.2 FEUM

What immediately can be noticed from the results of the FEUM penalty, is that over half of it is saved due to the WASP. This might seem striking that an alternative results in savings so significant but the image is distorted. That half of the cost is saved, is purely due to it being just over the boundary of the maximum value. It is explained by the fact that the FEUM regulation has specific percentages which define what the maximum intensity is of the GHG emission of a vessel. In 2025, this is a decrease of 2% compared to the reference value of 91.16 gCO2e/MJ of 2020, so 89.3368 gCO2e/MJ. The actual GHG intensity of the HLV Fairmaster (using an average input of the past three years) is just over this threshold: 94,12 gCO2e/MJ. Due to WASP giving a reduction of 3%, this comes down to a new actual GHG intensity of 91.12 gCO2e/MJ. This difference is over 50%.
So if the actual GHG intensity would be much higher, e.g. 110, then the WASP would make it 106.7. This number is obviously much higher than the threshold value of 89.3368 which the savings less significant in a relative sense. This is shown in table 16.

6.2.3 Board of Directors - Importance of ROI

In the process of doing research for this thesis, the board of directors has been interviewed in a structured way, in order to find how they rate the best-to-others and the others-to-worst for the BWM. As stated in section 4.2.4, they had to choose the most important (the best) and the least important criterion (worst). After the interview, each of them stated that the choice for the most important criterion was obvious: ROI. In the end, Jumbo Maritime is a commercial company and its main objective is to be financially healthy. Choosing solutions with a positive ROI is crucial in this and the lower the ROI, the better. This is the case since how longer it takes to pick the fruits from a certain solution, the better. In the end, the future is uncertain: it is dynamic and regulations might change. This is also shown by the changing of the IMO initiative regarding 2050 (see section 2.3). At first they wanted to reduce the emissions by 50% in 2050 compared to 2008, but then they changed it to 100%.
The reason of the Board was that every criterion would ultimately point to the same outcome since everything is incorporated in the ROI. But as seen in the colored scheme in figure 25, each criterion points to another ranking in terms of which one is the better alternative (with the current input).

Alternative	ROI	Oper. Flex.	Install	Oper. Prof	CRI
WASP					
Wavefoil					
ALS					
Hull cleaning					
Flipper Zipper					
PBCF					
Eco-control					
Heat recovery					

Table 25: Comparison of alternatives across different criteria (only colors applied)

For example the hull cleaning by Damen, it scores the best on the ROI but it scores in the middle of the ranking on operational flexibility and CRI. Then ALS scores the worst on ROI but it does not score the worst on operational flexibility, installation time and operational profile. And the last example: WASP, it scores a 7,17 standardized on ROI but it scores the worst on operational profile and reasonable high on operational flexibility.
Put simple: when observing the colored table, it becomes evident that no single row has the same color across all columns, particularly in relation to the ROI. This shows that the criteria are not fully reflected in the ROI.

Lastly, this can also be shown by putting the ROI ranking next to the final ranking of the DSS, as has been done in table 26. It is similar, which is logical since the ROI has a major weight (42%) in the calculation, but it is undeniably different. This shows the interdependency between the criteria is not significant.

Alternative	DSS	ROI
WASP	6,3	7,3
Wavefoil	3,2	2,8
ALS	3,5	1,0
Hull cleaning	9,2	10,0
Flipper Zipper	6,6	9,8
Propeller Boss Cap Fins	9,2	9,1
Eco-control	7,6	9,1
Heat recovery	7,0	7,5

Table 26: Comparison of the ranking of the DSS and ROI

6.2.4 Sensitivity analysis

Sensitivity analysis has shown that the DSS is very robust for changing input values. In this section, the results are discussed of the sensitivity analysis.

Initial input
In appendix A.18.1, the ranking can be seen of the measures when the initial input was varied with 15% or with other discrete values. It can be concluded that the rankings did not differ as a consequence of the different values of the fuel variables, the percentage it sails in the EU and the ETS price. The values differed, but the 15% resulted in no notable differences. However, the sailing days per year differed not at all. After investigating this, it was found out that this variable is only used in the calculation of the fuel-savings per year, FEUM savings and ETS savings per year. However, every measure is calculated per year so it does not

influence the final result. It is a useful metric for the ROI calculation of how high the ETS-, FEUM- and fuel-savings are. but for the ranking it does not make a difference.
Next, the WASP reward factor only has an influence only on the WASP. When it has its maximum value (5%), this is the only case on which it has an effect on the ranking. Overall, the sensitivity analysis has shown that it is a robust system. The rankings do not change significantly.

ROI
In Appendix A.18.2, the rankings of the different alternatives can be seen for the cases of 15% change in ROI compared to the base-case. From this, it can be concluded that the rankings remain largely unchanged, except in the case of the Wavefoil. This is reflected in table 20 in section 5.5.2, where Wavefoil shows the largest difference in score before and after a 25% change in ROI.

Wavefoil's ranking changed significantly because it had the lowest initial score, making it more sensitive to changes. In the DSS, scores are scaled relative to the highest and lowest values (standardization), so if the lowest score increases, it moves closer to the next-lowest, reducing the gap. But if the Wavefoil score drops further, the gap grows, making it more of an outlier.
Since Wavefoil was already at the bottom, even a small change in ROI had a bigger impact compared to alternatives with higher scores. The DSS standardizes all scores, meaning that changes in the highest or lowest values affect the entire ranking system. This effect became even stronger in the -25% case, where Wavefoil's score increased enough to pass the second-lowest alternative. This meant Wavefoil was no longer the lowest-ranked, reversing the standardization effect. Instead of being pulled further down, its position improved significantly. Because of this, Wavefoil's ranking shifted much more than others, while mid-range alternatives stayed more stable.

For the highest-ranking alternative, hull cleaning, no ranking change occurred at all. This is again due to the DSS structure: hull cleaning remained the highest-scoring alternative in terms of ROI across all scenarios. However, since it did not rank highest across all other criteria, it did not become the top-ranked alternative overall.

BWM weights
In appendix A.18.3, the rankings can be seen. One of the key insights from the analysis is the stability of certain alternatives, like hull cleaning and Propeller Boss Cap Fins which consistently rank high in all scenarios. This indicates that these options are robust performers and are less influenced by changes in the criteria's weights. Their strong performance under different conditions show that they are reliable choices regardless of the decision-makers' prioritization of criteria.
In contrast, other alternatives show significant variability in their rankings, so they are more sensible to weight changes. Wavefoil and ALS show to shift significantly in performance depending on the weighting scenario. This suggests that their effectiveness is dependent on specific criteria being prioritized. Such solutions may be beneficial in certain contexts but might not perform as well if the importance of those criteria lowers. This variability underscores the importance of aligning weight prioritization with strategic objectives when considering these options. Solutions such as Eco-control and Heat recovery exhibit moderate sensitivity, with their rankings slightly fluctuating based on weight changes, which show these trade-offs.

Fuel-saving percentages
The DSS output for different fuel-saving percentages is shown in Appendix A.18.4. These percentages directly affect the ROI, as both fuel-savings and ETS savings are calculated based on them. Fuel-savings depend on the amount of fuel (in metric tons) saved, while ETS savings are based on the reduction in CO2-eq emissions. Since ROI has a strong influence in the DSS, changes in fuel-saving percentages can significantly impact the results. The highest- and lowest-ranked alternatives show the biggest changes, while the mid-ranked alternatives are affected less.

The effect of standardization on the highest and lowest alternative is that the highest and lowest values set the comparison scale. This affects how differences between alternatives are measured: If the highest value decreases, the gap between alternatives shrinks, making all scores closer together. If the lowest value increases, the differences between alternatives narrow, reducing the impact of variations. This is visible in WASP, where a 2% change in the fuel-saving percentage leads to only a 0.3-point variation, when its ranking stays the same. For hull cleaning, the highest value, the effect is much stronger. If its fuel-saving percentage drops to 3% or lower, the ROI becomes negative, meaning the investment would not pay itself back. Since ROI has a large weight in the DSS, this causes hull cleaning's score to drop from 9.16 to 5.39, moving its ranking from second to sixth place. Thus, while standardization makes sure that the comparisons are fair, it also makes rankings highly sensitive to extreme values, causing some alternatives to be more affected than others. For the lowest-ranking alternatives, it also results in a big difference in scoring. If the fuel-saving percentages differ for the Wavefoil and ALS, it results in a change of the lowest alternative, due to the change in the Wavefoil score being significant: a difference of more than 2 points in the case of ALS being 3 and 7% fuel-savings. This can also be seen in figure 37.

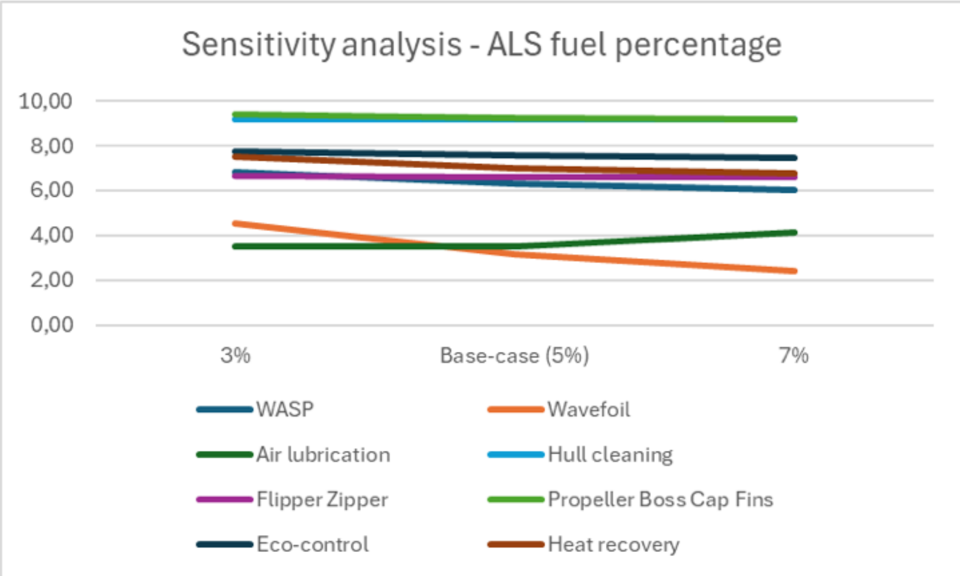

Figure 37: Sensitivity analysis - ALS fuel percentage

Why hull cleaning is more affected by fuel-savings percentages is due to its cost structure. Unlike other measures, hull cleaning has a low CAPEX but high OPEX. The 35000 EUR per session cost is part of operational expenses (OPEX), except the first session, that is part of the CAPEX. The reason for this is that if hull cleaning is chosen, the minimal amount of sessions is one, resulting in the specific fuel-saving percentage. Since this percentages degrades over the year, also the fuel-saving percentage decreases over the year. The optimal amount of sessions is assumed to be four. So, it four sessions are done, than the fuel-saving percentage holds over the whole year, but the last three sessions are part of the OPEX (as seen in table 27), since that is seen as maintaining the alternative, which is expensive. This is the only alternative where this happens. Then, if fuel-savings are too low due to a fuel-saving percentage that is too low, OPEX overpowers the savings, leading to a negative ROI. This makes hull cleaning more vulnerable to changes in fuel-saving assumptions, showing the importance of using accurate estimates in cost-effectiveness evaluations.

So, changing fuel percentages changes the scoring of the alternatives in the case of the highest and lowest ranking ones. But, over all, the ranking stays relatively consistent, especially for the alternatives scoring second to sixth place.

Alternative	**CAPEX**	**OPEX**	**Fuel-saving**	**ETS savings**
WASP	-750	-15	126	34
Wavefoil	-750	-35	139	37
ALS	-950	-15	126	34
Hull cleaning	-35	-105	151	41
Flipper Zipper	-30	-5	50	14
Propeller Boss Cap Fins	-125	-5	101	27
Eco-control	-100	0	76	20
Heat recovery	-400	0	151	41

Table 27: Overview of CAPEX, OPEX, fuel-savings, and ETS savings for each alternative (in 1000 EUR)

6.2.5 Verification

The DSS must be tested for functioning correctly and logically. This has been done with the changed inputs of the sensitivity analysis and other tests which are seen in appendix A.19. Different amounts of hull cleaning have been used, ranging from 0 to 10 when 4 was the ideal frequency per year. 0,2,4,6 times was done in the sensitivity analysis and this resulted in an increasing higher score. 0 times did correctly result in getting a score of 1, meaning it is the lowest, without influencing the other scores. This can be seen from the fact that the hull cleaning alternative gets the same score as the other lowest-scoring alternative on every criteria. Next, the resulting score (or any score) did not differ when the vessel was cleaned more than 4 times a year, which fits the real world situation since it can not achieve a higher fuel-saving percentage than 8% when using hull cleaning (figure 71).
The amount of fuel usage has also been changed to see if the DSS behaves accordingly. In the case that 0 fuel was used, it resulted in a FEUM penalty(saving) of 0,00 EUR, which makes sense since no fuel burned equals no emission, table 65. However, the ranking differed a lot. This is due to the standardized ROI score of every alternative being 1. This is also an assumption of the model, see section 6.3.3. No fuel was burned so also no fuel was saved and no ETS cost was saved. This means that the analysis was done purely focusing on the other four criteria. Hull cleaning and PBCF still came out first, and Wavefoil and ALS came out last.
In another scenario (table 18), where only an amount of 1000 mt/day of VLSFO was burned, it resulted in the same ranking as in the base-case. What did change, was the FEUM penalty (saving) which rose dramatically, which makes sense since a lot more fuel is burned. The actual GHG intensity was somewhat above the treshold, but the amount of emission was a lot bigger. This also explains why the proportion of WASP saving is so high (50%).
In table 66, a scenario was done in which there was a usage of 23 mt/day of VLSFO, 5 mt/day of MGO and 5 mt/day of biofuel. This scenario was interesting since it this amount resulted in an emission just over the FEUM target threshold. The WASP made sure that the intensity was just below the threshold which was otherwise exceeded. The test showed that the whole penalty was saved due to the WASP, which proves a functioning DSS.
Then, a scenario was done in which only biofuel was used, 30 mt/day which is a realistic number since on average 23 mt/day of VLSFO is used. This resulted in the same ranking but no FEUM costs, which is due to the fact that the FEUM target threshold of the EU is not exceeded, thus no penalty (table 67.
A scenario in which there was not sailed at all in the EU (0% of EU sailingtime, table 68), leaded to a lower score of the WASP. However, the ranking did not change at all. This shows that only the WASP is influenced by the WASP reward factor, as it is supposed to. This also checks out since the WASP reward factor is only impacted by sailingtime in the EU. In the opposite scenario, where the EU sailingtime is 100%, figure 69, the ranking is the same, except that the WASP has a higher score than in the base-case: now it has the same score as the Flipper-Zipper, showing again the influence of EU sailingtime on the WASP.
In table 70, a sailingtime of 0 days was chosen as input for the DSS. It gave an error on every kind of output. This makes sense because when the vessel is not sailing, the measures can not have any influence on the vessel.

Concluding the verification: the DSS functions correctly and logical.

6.2.6 MACC

From the MACC, it can be seen that Eco-control is the most cost-effective measure, while hull cleaning is the least cost-effective. Additionally, as stated, all alternatives have a negative cost, meaning they generate net savings per ton of CO2-eq reduced. However, the ranking of alternatives in the MACC differs from the DSS output.

Why the MACC and DSS rankings differ
The difference in rankings comes from how both methods evaluate cost-effectiveness. The MACC annualizes CAPEX, meaning that measures with a longer lifetime appear more cost-effective because their upfront investment is spread over multiple years. Lifetime plays a crucial role in this analysis: alternatives with a longer lifetime score better in the MACC than in the DSS.
In contrast, the DSS does not consider lifetime at all. Instead, the DSS ranking is strongly influenced by ROI, where CAPEX is a key factor. Since ROI carries a weight of 42%, measures with higher initial investments tend to rank lower, even if they result in cost savings over time. For example, hull cleaning has a lifetime of just one year when four cleaning sessions are performed, making its overall cost seem higher compared to measures with longer lifetimes. This explains why its ranking is lower in the DSS than in the MACC.
In addition, the MACC does not take the other criteria (e.g., installation time) into account, which makes sense since this is also not the goal of the MACC. It only aims at calculating the marginal cost of abating

emissions.

Results from the MACC

The MACC provides a different perspective by showing cost-effectiveness without being affected by the size of the initial investment. This is particularly impacting short-lifetime measures, like hull cleaning, which appear much less promising despite reducing emissions effectively.

Another key aspect of the MACC is that the width of each bar represents the potential impact of each measure in terms of total GHG reduction per year. This makes it clear that WASP has the highest potential for GHG reduction, while Flipper Zipper has the least. This highlights an important trade-off: some measures may be highly cost-effective but contribute less to overall GHG reductions, while others may have higher upfront costs but lead to greater long-term emission reductions.

Despite all alternatives showing negative costs (meaning they should be financially attractive) they are not widely adopted. This could be due to:

- Informational barriers, companies might not be fully aware of the savings potential or lack the knowledge to implement them effectively. This is changing now more and more researches are done with regard to decreasing the GHG emission, and since regulations become active which result in high costs: ETS and FEUM.
- Upfront investment constraints, even if a measure saves money in the long run, companies may struggle to finance the initial CAPEX. The classification criteria "maximum CAPEX" might still be high.
- Lack of incentives, without policy support or market-driven incentives, businesses may prioritize other investments with more immediate returns. This changes now regulations become active and companies are incentived to invest in measures like these.

According to the MACC, all alternatives analyzed are actually good options to implement. However, the differences between the MACC and DSS rankings highlight how different methodologies influence decision-making. This shows that when selecting measures, it is important not only to consider cost-effectiveness but also the total potential for emission reduction. So, financial viability, lifetime, and GHG reduction potential have to be considered to make the best decisions. This is why the MACC gives a great insight into which measure to select: it gives a different view by incorporating lifetime and annualizing the CAPEX (which is discounted).

The results of the DSS and MACC may differ, but there are big similarities in their final ranking. As can be seen in table 28, the PBCF and Eco-control are in the top 3, while ALS and Wavefoil are in the bottom 3. This shows that the outcomes are consistent, except for the hull cleaning, which has changed dramatically (due to the short lifetime).

Ranking	MACC	DSS
1	Eco-control	PBCF
2	PBCF	Hull cleaning
3	Flipper Zipper	Eco-control
4	Heat recovery	Heat recovery
5	WASP	Flipper Zipper
6	Wavefoil	WASP
7	ALS	ALS
8	Hull Cleaning	Wavefoil

Table 28: Ranking of the alternatives by the MACC compared to by the DSS

6.3 Limitations

When writing this thesis, limitations have become clear. These are important to discuss because they help explain the boundaries of the study and provide context for the results. Having the limitations clear, results in improving the transparency and reliability of the thesis. This includes finding out where the findings are strong and where they are limited.

6.3.1 Scope

This thesis has a specific scope. In a nutshell, the scope is on existing HLV and on reducing the GHG emission. This leads to only taking alternatives into consideration which are not too expensive since it needs to stay financially viable. Retrofitting is the goal but some alternatives were just too expensive and would never be possible. For example changing the engine in order that it can only use hydrogen or methanol. This is only an option for new building, as also discussed with the fleet department. But in order to play with alternative fuel in the tool, it was built in to use biofuel (instead of VLSFO or MGO). This has an impact on FEUM, ETS. Also, they needed to pass certain classification criteria, which are safety, regulatory compliance and TRL. As seen in the long list, appendix A.10, a lot of these are out of the scope. The selection which passed the classification criteria and did not need too much retrofitting, are used in this thesis. Also, the criteria are scoped on HLV, since they need as much free deck space as possible for the wide range of objects they need to transport, and travel to changing (unknown) destinations. Liners sail to the same places over and over, enabling them to built infrastructure at those ports, letting alternatives like carbon capture be an option. But when travelling to changing destinations, where there is no guarantee on sustainable fuels, or the possibility to switch filled carbon capture tanks to empty ones, a wide range of alternatives falls out of the scope.

6.3.2 Criteria scoring

The **ROI** is based on the cost of the alternative, regardless of its lifetime. This is an important aspect to keep in mind when using the DSS. Especially this is important when evaluting the hull cleaning alternative. Its costs are based on the savings and costs per year. Due to the significant fuel-saving percentage (6%), the savings are higher than the OPEX. But when calculating the costs of the alternative over, let's say, 10 years, than it costs 1,4 million EUR (4 times a year * 25 000 EUR * 10 years). This is far more than the WASP and Wavefoil, which get a lower score due to their low ROI. This is also why the MACC is a perfect addition to the DSS. This way of looking at an alternative does take lifetime into account.
The scores assigned to all criteria, except ROI, are based on literature research. As a result, they may not fully reflect the specific characteristics of the HLV Fairmaster, which serves as the reference vessel in this thesis.

The **Operational flexibility**, so how much the alternative has on the operation of the vessel, is based on logic and on information of the manufacturer. This can be biased since the manufacturer downplays how much it really influences the daily operation. For example the PBCF, they are fitted at the propellor, resulting in 0 influence on the daily operation of the vessel, giving it a 10. But WASP, has a 9, if fitted on the deckhouse. But if it is impossible to place it there due to structural feasibility for example, the score lowers dramatically. So, the scores are estimates and may change due to specific vessel characteristics or due to other circumstances.

The same applies to the **installation time** of the alternatives. The real installation time might differ from these numbers. The Wavefoil for instance, depends on project aspects like vessel size, existing design complexity and shipyard capabilities. Only one case has been found that gave a full installation time, and this has been used as the input.

The **operational profile** of a vessel depends on the specific routes it takes, which affects how well different alternatives perform. However, accurately modeling this is a complex task and falls outside the scope of this research. Instead, the scores are based on (academic) literature, which may not fully reflect real-world conditions.
To model route-specific factors accurately, variables like wind angle, wind power, vessel speed, and operating conditions would need to be considered. Since this is too complex, only general external factors have been used. These factors are averaged instead of assigned specific values per trip. For example, the score of Eco-control depends on route specifics and fuel types, while WASP is influenced by wind direction and power. This means the scores are generalized rather than tailored to specific routes. In reality, if a vessel often sails on routes with strong winds, its operational profile would score higher than if it operates in low-wind areas. Since routes always change, operational profile has not been included as a fixed factor in the decision support tool. This is key for companies like Jumbo Maritime, which operate wherever they are hired, making the operational profile unpredictable. Despite this, academic literature is based on verified sources, making the data reliable, even though it does not capture all route-specific details.

CRI also has been based on literature review. There is watched at how much competitors there are so if it is on a big scale, if there are multiple commercial applications, how big is the market competition, if it is a bankable asset class (see figure 53 in appendix A.11.5). Derived from this information, a score is given. But this score can be somewhat lower or higher, dependent on the available literature. An concept like Wavefoil might take off in the near future and then be adopted big time, resulting in a different score.

6.3.3 Assumptions

Making assumptions is inevitable in doing research due to having to complete the thesis within time and resource limits. But they also create limitations that can affect the accuracy of results. This can make the results less reliable or less applicable to specific cases. To keep this thesis transparent, the assumptions that have been done are described below.

- Fuel-saving percentages are based on academic literature and insights from Jumbo Maritime, as shown in Appendix A.14. However, the actual efficiency of these alternatives in real-world use is uncertain due to changing vessel conditions, weather, and operational factors. To test this, it has been changed sensitivity analysis to see how different fuel-saving percentages affect the results. This ensures that the conclusions remain reliable, even if real-world performance differs from the estimates. To optimize this percentage, the operational profile must be digitalized and from this, also an accurate fuel-savings percentage can be deducted.

- The ROI is based on CAPEX, OPEX, fuel-savings, ETS savings and FEUM penalty savings. The operational profile has thus no influence on ROI.

- Fuel-saving percentages per alternative are aggregated across different fuels. The reason for this is that a major part of the sources do not specify which fuel is used as a reference when stating a specific saving percentage. VLSFO is the most widely used marine fuel post-IMO 2020 regulations due to its compliance with the sulfur cap. So savings percentages in literature post-2020, are often referenced against this fuel-type. In older literature, HFO is used as a reference since it was most used on oceangoing vessels but it's less common due to the SOx regulations. The solution for this is to calculate in energy equivalence in the unit MJ, instead of per ton of VLSFO. This makes the savings more accurate and definitely more broadly applicable regardless of the fuel used. The scope of this thesis was to focus on the DSS. In the end, the fuel-saving percentages per alternatives are input of the model.

- The classification criteria maximum CAPEX, has been set on 1 million EUR. This is due to budget constraints that exist within Jumbo Maritime, being a "small but brave player in the maritime market", as stated by the Operational Director of Jumbo Maritime. He also stated in his interview (seen in appendix B.8), above 1 million EUR, the supervisory board has to decide if the investment is worth it, and they have been left out of the scope of this thesis, since they have not been interviewed. Also, there is not as much room for error to invest in a measure above 1 million EUR that may fail. This hangs together with the TRL classification criterion. But due to the maximum CAPEX classification criterion, big retrofits automatically fall out of the scope of this thesis, like another engine. This is also what Jumbo Maritime wanted from this thesis: no big retrofits since that is reserved for new build vessels.

- Ideally, hull cleaning is done 4 times a year to have a fuel-saving percentage of 8%. When there is cleaned less than 3 times a year, the fuel-saving percentage drops linearly. If the hull is cleaned more than 4 times a year, the fuel-saving percentage stays on 8%, since that is the fraction of fuel-use that it potentially can save. The input value is also 4 times a year because it is assumed that if hull cleaning is chosen, it will be executed in the ideal case of 4 cleanings per year.
  If the hull cleaning measure is not chosen, it will also not have an impact on the scores of the other measures and it will have a score of 1 on every criteria. This is done by putting the input to 0 at "Hull cleanings time per year". This is done at the sensitivity analysis, this result can be seen in appendix A.18 in table 40.
  Also, the CAPEX consists of one time the hull cleaning costs (35 000 EUR). This is due to the reason that if the alternative is chosen, the cleaning times are at a minimum of 1 time a year. The extra hull cleaning times per year (1,2,3), are placed in the OPEX, since it is for keeping the hull clean after the first session.

- Lifetimes of the different measures are estimated for the generation of the MACC. This makes hull cleaning low in the MACC since the costs are annualized. For other alternatives, like WASP, the CAPEX is spread out over a lifetime of 15 years.

- Subsidies are not calculated and used in the DSS. This was not in the scope of this thesis and it was not deemed as having a significant impact. The subsidy would have to be considerably high if this would make the difference between being a potential promising measure and not being a potential promising measure.

- Values of the performance matrix are standardized, meaning their score is relative to the highest and lowest score in that criterion. This makes the final score fall between 1 and 10.
- The HLV Fairmaster performs the same on every trip it makes with regard to environmental conditions which may not reflect the real-world situation. In the case study, the fuel usage has been averaged over the past three years (2022-2024) to ensure reliability. The percentage it has sailed in the EU, has been averaged over the past five years (2019-2024), just as the distance sailed (according to the AIS).
- A discount rate of 5% has been chosen which reflects how much future costs and savings are worth today. It is necessary to have a difference between costs (CAPEX+OPEX) and benefits (savings on FEUM and ETS) now and later due to inflation and uncertainty in terms of value. This is used in the MACC and 5% is a common value in environmental analysis'.
- If the ROI is bigger than 20 years or negative, the DSS gives it automatically a ROI score of 1 in the standardized performance matrix. This is done so the other alternatives are not influenced by this ROI. Also, a ROI bigger than 20 years is not a feasible option, due to the focus on existing vessels. In 20 years time, these vessels are outdated and the further it is in the future, the more uncertain it is. A ROI that is negative means it will never pay itself back, hence the score of 1.
- The ROI values are estimated as accurately as possible, based on literature and information within Jumbo Maritime. This influences the ROI and since the ROI has a heavy BWM weight, it influences the whole DSS output. However, ROI needed to be calculated since it is so important in the decision on which measure to implement. But in order to test how much it would matter if the values differ, a sensitivity analysis has been done.
- Reputation has not been brought into the DSS since it is not yet important, according to the interviewed stakeholders. However, this will be important in the future.

7 Conclusion

In conclusion, this section summarizes the key findings of the thesis by answering the research questions, providing recommendations, and offers suggestions for future research. This thesis is finished with a final statement.

This thesis focused on the reduction of GHG emission from existing HLV vessels, since this was not yet been researched. HLV are different from ordinary carriers due to them being characterized by needing maximum free deck-space and having irregular destinations. In this thesis, a structure was generated which went into the decision on which measure was the best on decreasing the GHG emission and what drives this decision, with regard to criteria and their relative importance over each other. Due to the newly implemented regulations of the EU and IMO, this topic gets an increasing amount of attention, especially since financial penalties are at play. This has led to the main research question:

Which technological innovations are best suited for heavy-lift vessels in alignment with the objectives of Jumbo Maritime, the EU and the IMO for reducing greenhouse gas emissions?

7.1 Answers to the research questions

To answer the main research question, first the sub research questions are answered which are based on the objectives of Jumbo Maritime. These are stated below, together with their answers. Afterwards, the answer to the main research question is given.

7.1.1 Sub research questions

1. *What is the current state of the IMO and EU regulations on reducing greenhouse gas emissions in 2024, and how are they related?*
   In section 2.3 and section 2.4 the current initiatives of the IMO and EU are discussed. It was shown that the IMO and EU regulations are interconnected in their shared objective to decarbonize maritime transport by becoming net-zero in GHG emissions by 2050.
   The EU has the ETS, which has become extended to shipping in 2024; FEUM, which sets a limit on the GHG intensity of vessels, active from 2025; and MRV, used for reporting of GHG emissions from vessels, also from 2024. Companies like Jumbo Maritime also have to report on their sustainability goals and activities with the CSRD from 2026.
   The IMO also has initiatives but there does not exist a standardized enforcement mechanism for vessels with lower ratings or non-compliance. These are the CII, a rating system calculated on the amount of grams of CO2 emitted per cargo-carrying capacity and nautical mile, active since 2023; the EEXI/EEDI, which is a benchmark on the energy efficiency of a vessel, also from 2023; the SEEMP, which entails a management plan and for report data in the DCS for energy efficiency. Important to note is that HLV are excluded from the scope of CII and EEXI. The expectation is however that the IMO will introduce financial penalties (similar to the EU regulations) in the future. But, individual port states can potentially restrict the access or give other penalties.

2. *What sustainable measures can heavy-lift vessels adopt to reduce GHG emissions in compliance with IMO and EU regulations while remaining economically viable?*
   Eight measures have passed the classification criteria in order to be analyzed in the DSS. These are: the WASP; Wavefoil; ALS; Hull cleaning; Flipper Zipper; Propeller Boss Cap Fins; Eco-control; and Heat recovery.
   The classification criteria are: safety, regulatory compliance, TRL and maximum CAPEX (< 1 million EUR). Safety is particularly crucial to Jumbo Maritime, seen its Stay Well program which shows its role as a fundamental company value; the measures have to reduce the GHG emission of a vessel; they have to be proven technologies, Jumbo Maritime is too small to experiment with expensive measures; and a maximum CAPEX of 1 million EUR. From a longlist, depicted in appendix A.10, this shorter list has been made.

3. *What are the relevant criteria that influence the decision on whether a sustainable technology is a promising innovation which fits the financial mission of Jumbo Maritime and what is their relative importance*
   In semi-structured interviews with the relevant department managers: it was found out that the relevant criteria were: ROI, operational flexibility, installation time, operational profile and TRL.

ROI is the most important factor, as financial viability and a shorter payback period are essential for a positive decision due to more certainty and for the business case. Without a positive business case, decision-makers are unlikely to implement a measure. Operational flexibility must be maintained, meaning solutions should not interfere with crucial vessel operations and characteristics, such as crane operations or free deck space. Installation time is also critical, with changes ideally planned during drydock to avoid delays and extra costs. Measures should align with the vessel's operational profile for positive effect, it should match the unpredictable routes and loads to improve efficiency and reduce emissions. The TRL is important to ensure the technology is reliable and ready to use. Compliance with regulations such as FEUM and ETS is a major driver, as companies must meet standards to stay competitive. This is also why it was used as a classification criteria, seen that this is a the scope of this thesis. Safety (another classification criteria) was also seen as crucial, seen the core value of Jumbo Maritime, with its Stay Well program. Lastly, reputation is increasingly important, as clients and employees value environmentally responsible practices. However, this was not seemed as significant enough (yet).
This makes the definition of "best suited" in the main research question mean that it depends the most on the ROI (42%), followed by Operational flexibility (24%), Operational profile (13%), CRI (11%) and lastly, Installation time (8%).

4. *Which measures that decrease GHG emissions are the best choice in terms of robustness and viability for Jumbo Maritime's HLV Fairmaster?*
The sensitivity analysis and verification tests confirm that the DSS shows to give reliable and logical rankings for selecting GHG reducing measures for Jumbo Maritime's HLV Fairmaster. Hull cleaning and PBCF consistently emerge as the most robust and viable options across different scenarios, which shows stability regardless of input variations. In contrast, Wavefoil and ALS rank the lowest, showing higher sensitivity to changes in assumptions and input values. The standardization method ensures that rankings remain meaningful but also makes extreme values have more impact.
Verification tests further validate the DSS's correctness. Different scenarios, such as varying the number of hull cleaning sessions, fuel usage, and EU sailing time, all produced expected outcomes, confirming the system's logic. Also, important to note, reducing the EU sailing time lowered the WASP final score but did not change the overall ranking, confirming that only WASP is influenced by this factor due to FEUM (which only has an effect on WASP). Additionally, the DSS correctly identified that no fuel usage results in zero emissions and penalties, and that biofuel-only scenarios eliminated FEUM costs entirely. These findings confirm that the DSS effectively evaluates GHG reduction measures, with hull cleaning and PBCF being the most reliable choices. The methodology is sound, and the tool's output remains consistent and logical under different conditions.

Now the sub research questions are answered, the main research question can be answered.

7.1.2 Main research question

The answer on which technological innovations are best suited for heavy-lift vessels in alignment with the objectives of Jumbo Maritime, the EU and the IMO for reducing greenhouse gas emissions, depends on how the question is asked.

Answer depending on criteria
If the question is posed as initially was meant, which defines "best suited" as what is valued as most important by Jumbo Maritime, this mainly (42%) depends on the ROI, among other criteria. These criteria have been answered in the third sub research question, and this is exactly what the DSS is designed to calculate.

Propeller Boss Cap Fins
The DSS showed that the PBCF is the first-best alternative to implement aboard HLV. This is the low hanging fruit where Jumbo Maritime can profit a lot from. This has been shown with the MACC, verification tests with changed input, sensitivity analysis' on different input variables, and with the standard input from the case-study on the HLV Fairmaster. It has consistently shown to be in the top of the ranking with almost constantly scores above the 9. It also has a lower CAPEX: it is between the 100 000 to 150 000 EUR. OPEX are low (5 000 EUR a year) which mainly consists of ordinary maintenance that has to be done either way on the propeller cap. Savings are significant, resulting in a ROI of approximately 1 year. It also can count on a high score on operational flexibility, since it does not influence any process on board, low installation time (1 day) which can even be done underwater. It also has no negative effect on operational profile and lastly, it is a proven technology: it has been installed on over 3500 vessels in 2020 (Mandra, 2020).

Also, other measures that GHG emission are promising and worth considering. Starting with the **Eco-control**, this has already been implemented aboard the HLV Jubilee of Jumbo Maritime. From the MACC, it can be seen that it comes out as the most cost-effective option by resulting in the biggest savings while decreasing GHG emission. From the DSS output, it comes out as the third-best as it has a high percentage of fuel-savings by improved efficiency (7%), resulting in a relatively short ROI period of a little over one year. The CAPEX is 160 000 EUR which makes it relatively accessible. It also has a short installation time and scores well on operational flexibility by not influencing the daily operations. On the operational profile, it may lead to a lower average sailing speed. However, if this is agreed upon by the client, it will not pose any problem. Also, it is not the best proven technology by scoring a 3 on CRI (on a scale from 1 being low and 6 being the highest): it has reliable manufacturers like MAN and Wärtsilä but it is not widely implemented yet. It is upcoming though.
Next, the **hull cleaning** proves to be a promising alternative. The DSS shows it is a very good measure to decrease the GHG emission, having a final output of 9.2. The hull cleaning process is approximated to take 12 hours, according to the actual hull cleaning processes of Damen, which is very short and results in significant fuel-savings. Also, on the other criteria it has a very high score. But hull cleaning emerges as the worst alternative in the MACC. It still results in negative costs when reducing the GHG emission which means that it ultimately saves money. However, in the MACC, costs are annualized. Since the process needs to be repeated multiple times per year to maintain fuel-saving benefits, the cumulative cost of each cycle makes this an very expensive alternative in the long run. The lifetime is thus very short. Other alternatives have a long lifetime which makes their annualized costs lower. This valuable insight proves that it is more expensive than the other alternatives overall, something the DSS does not account for.
The **WASP, Heat recovery and Flipper Zipper** are also seen as alternatives which can be implemented but their score was intermediate consistently in both the DSS as in the MACC. Flipper Zipper has a low cost but also a low return. The big downside of Heat recovery is that is has a high CAPEX (600 000 EUR) while the benefits are good, so this is really a strategy decision. WASP also has a high CAPEX 750 000 EUR, but it might result in big advantages due to the FEUM reward factor, possibility on subsidy, and the effect it has on reputation. But again, reputation was not seen as important and next to that, it has a significant installation time and for the effect of FEUM, it has to sail in the EU. So again, it depends on strategy.

Answer depending on strategy

During the process of doing this research, it became apparent that the answer to the main research question is more difficult than simply investigating how the criteria are valued. Since the regulations currently have become active, and more might follow with more financial incentives (of the IMO), a strategy must be made with a decarbonisation roadmap. This has also been shown in the interviews, with the manager of the Technical Department for example: "the key is to develop a clear strategy or roadmap that outlines our sustainability goals, the steps we need to take, and the resources required to achieve them." (appendix B.6). It is getting increasingly difficult to comply to the regulations since they are getting more strict by the decade. The end goal of the IMO and EU is to become net-zero on the emission of GHG emission of the maritime sector by 2050. This makes that shipping companies have to have a plan, or better: a roadmap, on how to achieve this. Already, there are mandatory actions that shipping companies have to do by the IMO and EU. The IMO demands that every vessels reports their emissions for the IMO DCS and that every vessel has a SEEMP, which is a management plan on how to improve its energy efficiency. By the EU it is mandatory to report the emissions as well in the EU MRV and that shipping companies pay for their GHG emission (ETS) and for their GHG intensity (FEUM). In addition, shipping companies must report on their sustainability goals and initiatives in the CSRD.
This makes that a roadmap is undeniably needed, which contains strategy decisions like when to decrease a certain amount of GHG emission. A specific amount of decreasing GHG can be achieved by implementing a specific kind of alternative. WASP is the best decision when a big reduce is wanted, since the MACC shows this has the greatest amount of decreasing potential. Or the other way around, if a small reduce is wanted for a low price, the Flipper Zipper can be the best decision. It depends on what the strategy is.

7.2 Recommendations

This thesis has demonstrated how decision-making should be structured when implementing measures aimed at reducing GHG emissions. This structure has been developed in the form of a DSS, which showed that the PBCF are the most promising solution on every aspect. However, in order to optimize the DSS, a digital operational profile must be created in order to find the right measure for the right vessel. Also, a key finding is that the selection process is highly dependent on the overarching strategy adopted by Jumbo Maritime. To ensure effective implementation, this strategy should be clearly structured in the form of a decarbonisation roadmap. Strategic decisions need to be made, such as using the possibility of pooling. Also, using shore-power (if possible) is very low hanging fruit which reduces the GHG emission.

7.2.1 Decarbonisation roadmap

A decarbonisation roadmap would outline specific milestones, including target dates and corresponding GHG reduction percentages. DNV has also generated one, as seen in figure 38. Based on these targets, business cases can be developed to identify and evaluate the most suitable measures for achieving the desired reductions. In this process, both the MACC and the DSS play complementary roles. The MACC helps determine which measures to prioritize for achieving a given reduction target. WASP, for instance, stands out as the measure with the highest reduction potential. Meanwhile, the DSS evaluates how each selected alternative aligns with the criteria valued by key stakeholders. When consensus is reached, this provides valuable input for the final decision-making process.
In this roadmap, strategy decisions have to be made as well. The amount of time a vessel sails in the EU time is leading. If specific vessels are set to sail solely in the EU and other vessels on different parts of the world, the decision can be made to make the EU sailing vessels more sustainable, since they are subject to the EU regulations. WASP is then an option due to the WASP reward factor which has a substantial influence on the FEUM penalty. Also, pooling is an option which is decision that can be made to influence the FEUM penalty. The alliance partners of Jumbo Maritime, namely Intermarine and SAL Heavy-Lift, can be used for pooling. When the EU vessels are adjusted to emit less GHG than the threshold demands, there exists a surplus which can be used to compensate other vessels within the same pooling in order to comply to the regulation. The use of biofuels and other more sustainable fuels is also an option to comply to the regulations, however, they are more expensive than the regular VLSFO.

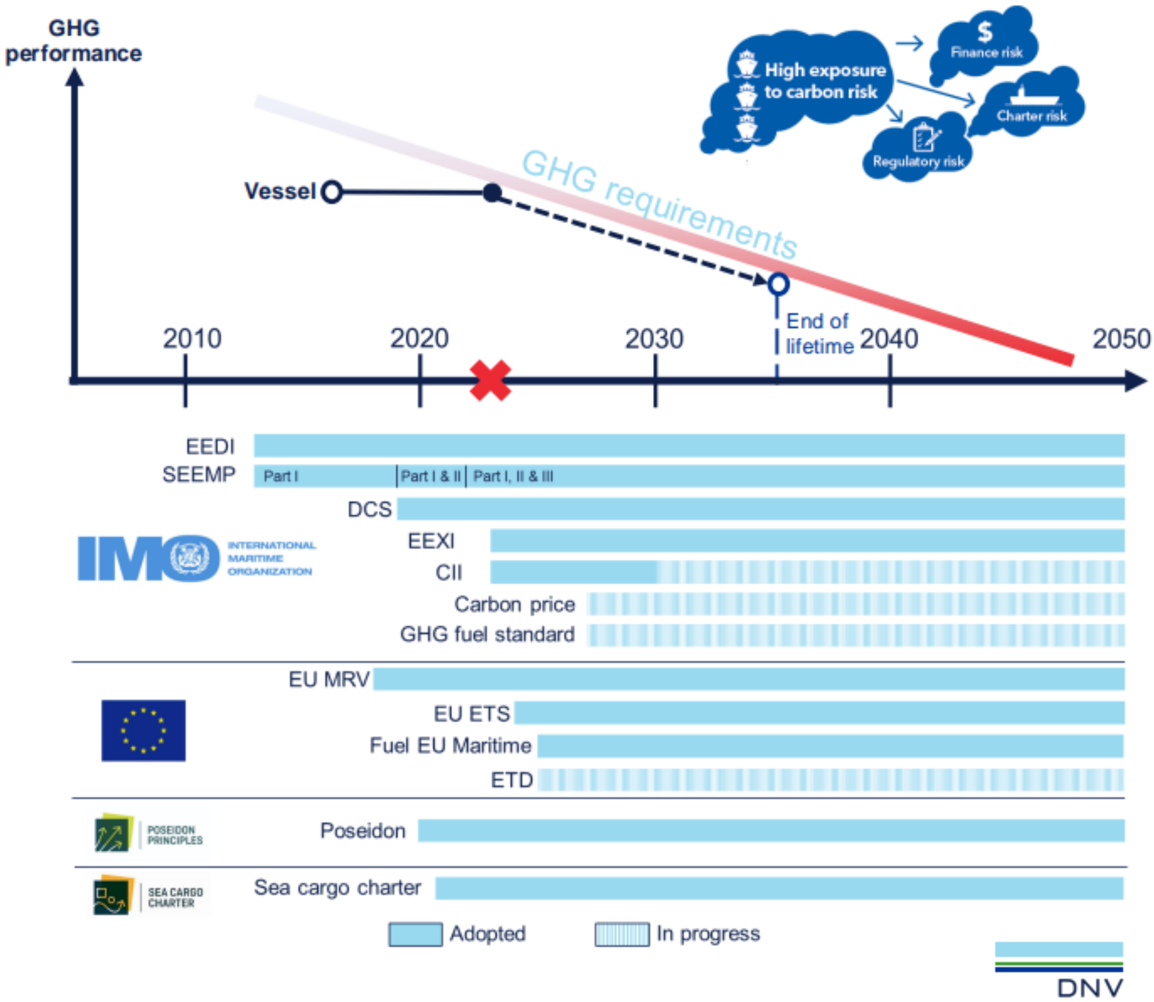

Figure 38: Roadmap for vessel decarbonisation (Source: DNV 2024, author received this via e-mail)

7.2.2 Opportunities to decrease FEUM penalty

FEUM introduces increasingly stringent targets, requiring operators to adopt cleaner fuels such as LNG, biofuels, or hydrogen-based alternatives. Meeting these targets will demand significant investments in technologies. However, energy-efficiency measures not only reduce emissions but also lower the demand for carbon-neutral fuels, making them a cost-effective solution (DNV, 2024a).
FEUM gives multiple options to decrease its penalty, which are interesting to look into. These are the so-called FEUM reward factors. The first option is to install WASP, which gives a discount on the GHG intensity of up to 5%. Secondly, when Renewable Fuels of Non-Biological Origin (RFNBO) are used between 2025-2032, the GHG intensity will be halved when calculating the actual GHG intensity of the energy used on board ships. Lastly, if onshore power is used when docked, this energy will not count towards the GHG intensity of the vessel. Next to the reward factor, also pooling is a interesting option to look into: if one vessel is below the threshold, its surplus can be attributed to another vessel which is in the same pool.

7.2.3 Motivational drivers for becoming more sustainable

So, firstly, costs are a key reason to make Jumbo Maritime's vessels more sustainable in terms of GHG emissions. This is reflected in the high weight (42%) that board members give to the financial criterion. The EU regulations ETS and FEUM already include financial incentives through emission trading certificates or penalties. The IMO is also expected to introduce financial incentives soon, making it important to act now as these measures will have a global impact.
Next, regulations are crucial because they go beyond financial penalties. Companies must report their actual emissions to the EU (MRV) and the IMO (DCS). The EU also requires companies to set reduction targets and outline their plans in the CSRD for 2026. The IMO has already introduced the SEEMP to improve vessel sustainability, and in the future, HLV will be included in its CII and EEXI regulations.
Lastly, an aspect that has not received enough attention is reputation and the accompanying market pressure. This pressure comes from three key stakeholders: clients, financiers, and employees. Starting with clients, it is clear that sustainability influences their perception when choosing a shipping company. If Jumbo Maritime demonstrates a strong commitment to reducing GHG emissions, it gains a competitive advantage over less sustainable shippers. An even stronger effect may be observed among financiers. While clients often focus on shipping costs, financiers prioritize a company's mission and long-term strategy. A company without a structured plan for financial and environmental sustainability may struggle to earn their trust. They prefer investing in a company that is future-proof. However, the strongest impact of reputation is seen in attracting employees. People want to work for a company that shares their values. They want to work in a company they can be proud of: organizations that actively contribute to a sustainable future.

7.2.4 Main recommendations

To accelerate the transition toward sustainable shipping, the following actions are recommended:

- Installation of Propeller Boss Cap Fins (PBCF);
- Development of a structured decarbonisation roadmap until 2050;
- Creation of a digitalized operational profile for enhanced fleet management;
- Utilization of OPS (Onshore Power Supply) instead of using auxiliary engines (incentivized under FEUM).

7.3 Further research

This thesis has examined how Jumbo Maritime can become future-proof in terms of sustainability while considering financial constraints. However, to further optimize the structuring of the decision-making process with the DSS, additional research is needed on several key aspects.
Firstly, it is essential to conduct interviews with the supervisory board to understand their perspectives on making the fleet future-proof. As this board oversees the management board's policies and the overall direction of the company, their input is crucial in defining the strategic approach to sustainability.
Secondly, the operational profile of vessels needs further optimization. While data from Hullkeeper and We4Sea is valuable, a digital profile needs to be created. This profile can also consider additional factors, such as the block coefficient. Engineers should evaluate how cargo resistance impacts efficiency and buoyancy and explore whether alternative routes could improve performance. **Digitalization** plays a crucial role in this

process, as a digital profile provides valuable insights into routing, energy consumption, emissions reduction, and fuel-savings when testing alternative strategies. It enhances transparency and with stricter emissions reporting requirements of the EU and IMO, digital verification tools will facilitate this digitalization and build trust.
Thirdly, increased awareness can significantly impact fuel consumption. Research by Jensen et al. (2017), based on full-mission simulator tests at the International Maritime Academy SIMAC, demonstrated that behavioral adjustments alone resulted in an average fuel-savings of 10%. This finding highlights the importance of training and promoting an energy-conscious culture within the organization.
Lastly, the potential influence of bias in stakeholder decisions must be further investigated. While this topic has been addressed in section 6.1, additional research is needed to determine the extent to which biases may have affected decision-making.

7.3.1 Newbuilding considerations

For newbuild vessels, several energy-saving and emission-reducing measures should be investigated:

- Adoption of electric solutions (e.g. LED lighting, digitalization);
- Implementation of ALS (commonly used in modern shipbuilding (Fotopoulos and Margaris, 2020));
- Installation of solar panels (Tuswan et al., 2022) (on the deckhouse will result in no loss of free space);
- Integration of onboard carbon capture technology, see section 3.5.2 (e.g. the Filtree system);
- Optimization of hull design (e.g., modified bulb);
- Utilization of alternative fuels (Xing et al., 2021):
  - Nuclear;
  - Methanol;
  - LNG;
  - Hydrogen.
- Implementation of kinetic energy recovery systems (e.g. recovering energy from crane lowering or jacking operations (Bergmann, 2024)).

7.4 Reflection and Final statement

In this concluding section, there is reflected on the thesis and a final remark is made to Jumbo Maritime on how to be future-proof.

7.4.1 Reflection on the Research Process

The primary objective of this thesis was to develop and apply a techno-economic model to evaluate both the technical performance and economic feasibility of various technologies aimed at reducing GHG emissions from HLVs. This model integrates technical factors (energy efficiency, emissions reduction, operational performance) with economic considerations (CAPEX, OPEX, MACC) to assess trade-offs between technology performance and financial viability. Ultimately, for a company to be future-proof, it must remain financially sustainable.

The research followed a mixed-methods approach, combining qualitative insights from stakeholder interviews with quantitative analysis using BWM. This approach provided a comprehensive perspective that incorporated the views of key stakeholders involved in decision making. From department managers defining critical criteria to the trade-offs considered by the board of directors. Additionally, answering the research questions has clarified the relevant regulations, identifying both those already active and those expected to take force. Furthermore, it has highlighted key constraints that any potential measures must meet to qualify, as outlined in classification criteria.

A significant number of assumptions were made due to the complexity of developing a structured DSS. This is also why this thesis operates at a higher abstract level rather than a purely technical or operational level. For example, fuel-saving percentages were estimated and aggregated, and the operational profile was simplified based on a literature review. Ultimately, the goal was to identify the key considerations and integrate them into a structured model. This objective has been successfully achieved. Future research should focus on improving (and validating) these assumptions, based on real-world data, and in this way transition from a higher abstract level to a more practical and data-driven decision-making tool.

Behavioral considerations have been analyzed in this research. A common risk in stakeholder-based research is subjectivity. Cognitive and motivational biases may have influenced the identification of criteria. However, the involvement of multiple interviewees, who identified similar criteria, shows a higher level of objectivity. Additionally, the consistency in input from board members indicates that the weights were calculated objectively. External specialists have also been used, such as DNV, to ensure reliable input.

7.4.2 Addressing the Problem Statement and Research Gap

The research gap went into the decarbonisation of HLV. There was no research whatsoever on this specific type of oceangoing vessels, which is relevant since they have certain characteristics that distinguishes them from other ones, such as the necessity for free deck space and having irregular destinations. What also was included in this research gap, is the similarity of the maritime sector on the challenge of how to choose the best alternative for their vessels in order to decrease their GHG emission.
The conclusion addresses this gap by demonstrating that the optimal measure to implement aboard HLV depends on the company's strategy. Since each company has its own strategic approach, this must be structured into a decarbonisation roadmap. Once specific milestones are defined, along with their corresponding budgets, a clear tactical plan can be executed to achieve these goals. For HLV, this depends on their specific characteristics, which involves irregular destinations. However, for the broader maritime sector, the approach can be generalized by developing a decarbonisation roadmap and using tools such as the DSS to weigh criteria and identify the most suitable measures. This structured approach ensures that decision-making is both strategic and data-driven.

7.4.3 Connection to the MSc. program

The MSc. Transport, Infrastructure & Logistics-program focuses on letting the student learn how to design, develop and maintain cost-effective, efficient systems for moving passengers and freight. "TIL graduates are able to make appropriate decisions for clients, employers and society, because they understand the complex decision-making processes during infrastructure development and planning." (TU-Delft, 2024).
This thesis goes into how a client can be future proof in a changing regulatory environment, with regard to making decisions in this complex climate. In this process, a tool has been designed in order to be cost-effective in a maritime sector that moves freight. What immediately can be seen is that multiple terms come back literally, which shows the direct relation to the MSc. program: decision-making in a complex environment, cost-effective system for moving freight for a client.
This MSc. program is part of three faculties of the TU Delft: Mechanical Engineering; Technology, Policy and Management; and the main-faculty, Civil Engineering. All three of these faculties have played a part in this thesis. Mechanical Engineering, by being a technological research with a focus on the maritime sector (Marine Technology). Technology, Policy and Management, it is a research that goes into the policy of a company with regard to decision-making. Tools that have been learned in courses of this faculty have been used, such as the BWM. Civil Engineering has also played a role, since it is about a system that goes into the transportation of goods.

7.4.4 Final remark

Looking to the future, decision-making must be data-driven, focusing on the operational profile of the vessels, regulatory developments, and reputational impacts. Clear communication and internal alignment will be essential for successful implementation. By integrating these findings, future research can support the development of a robust, future-proof sustainability strategy for Jumbo Maritime. They should not allow cost limitations to hinder its progress. Future-proofing extends beyond financial constraints: it is about securing both the company's long-term viability and the future of our shared planet. Employees are more engaged when they believe in their company's mission, making sustainability not just a responsibility but a strategic advantage. **"Limitations are perceptions"**: what seems like a constraint today may simply be a challenge to overcome tomorrow with the right mindset. By embracing innovation and committing to sustainability, Jumbo Maritime can ensure its resilience and leadership in the maritime industry.

8 Planning

Below, in figure 39, the Gantt-chart can be seen in which the planning of the graduation project is depicted. A legend for this chart is shown in figure 40. The milestone meetings were scheduled in September and remain unchanged.

Milestone	Week number	Date
Start research project	39	September 23rd, 2024
Kick-off	43	October 23rd, 2024
Midterm	51	December 18th, 2024
Greenlight	8	February 21st, 2025
Defence	12	March 21st, 2025

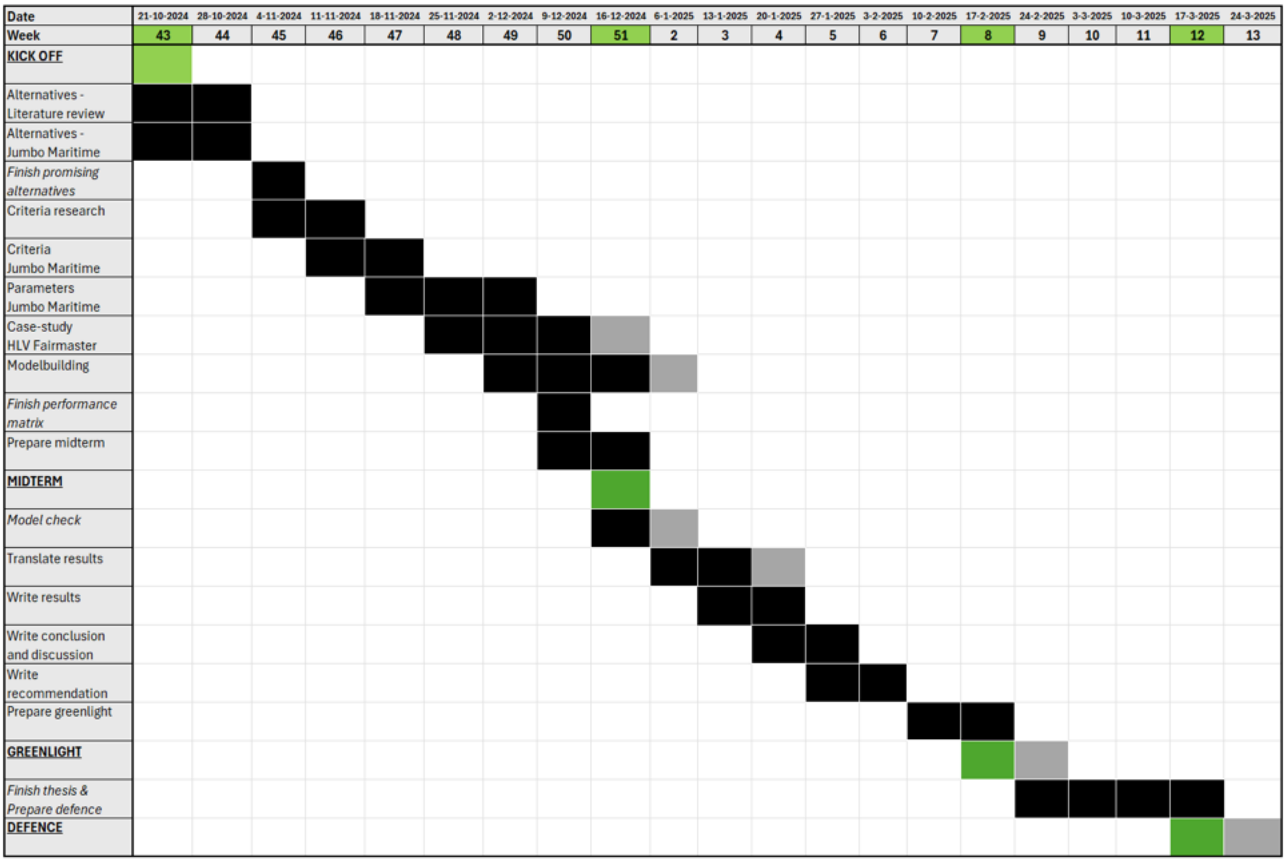

Figure 39: Flowchart Thesis

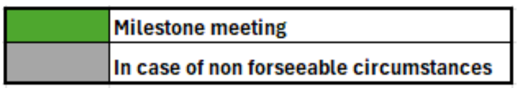

Figure 40: Legend Gantt-chart

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