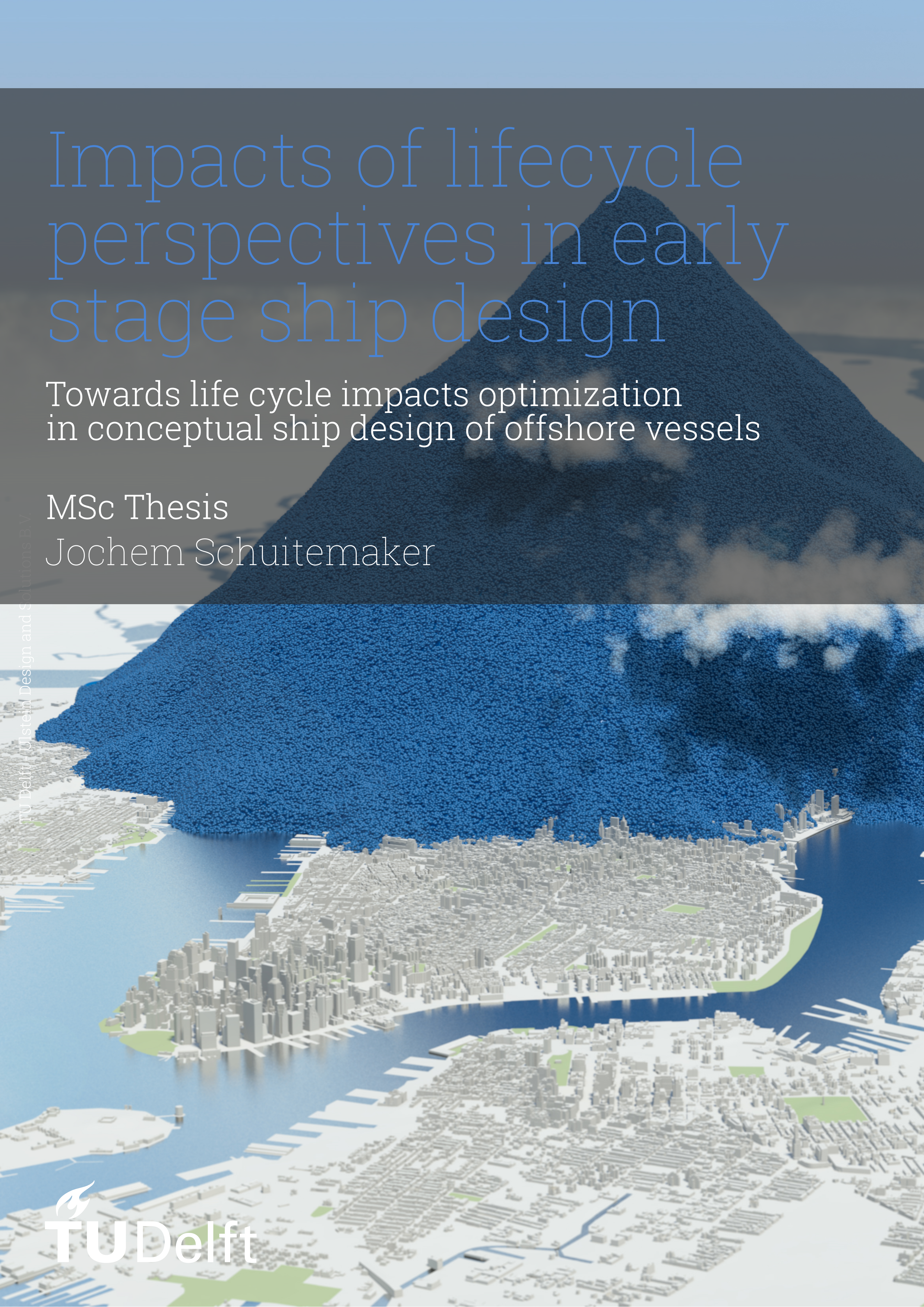

Impacts of lifecycle perspectives in early stage ship design

Towards life cycle impacts optimization in conceptual ship design of offshore vessels

MSc Thesis

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TU Delft - Ulstein Design and Solutions B.V.

Thesis for the degree of MSc in Marine Technology in the specialization of *Ship Design*

Impacts of lifecycle perspectives in early stage ship design

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by

Jochem Schuitemaker

Performed at

Ulstein Design & Solutions B.V.

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Cover: One day's carbon dioxide emissions from above (2012), Animation by A-Productions, retrieved from Flickr [1]

Preface

This report marks the culmination of my master's thesis project, undertaken as part of the MSc program in Marine Technology at TU Delft, in collaboration with Ulstein Design & Solutions B.V. The project explores the integration of Life Cycle Assessments (LCA) into the conceptual design phase of complex offshore vessels. This innovative research seeks to expand traditional design paradigms by incorporating environmental and economic impacts across a vessel's entire lifecycle—construction, operation, and decommissioning.

The journey to completing this research has been both challenging and rewarding. It required analytical thinking, theoretical insights from sustainable engineering, the application of advanced design tools, and the evaluation of real-world design implications. Collaborating with experts from academia and industry enriched the process, offering valuable perspectives that shaped the direction of this work.

I would like to extend my heartfelt gratitude to my supervisors, Dr. A.A. Kana from TU Delft and Ir. J.D. Stroo from Ulstein Design & Solutions B.V., for their guidance, constructive feedback, and unwavering support throughout this project. Their expertise and encouragement have been instrumental in achieving the project's objectives. I would also like to thank my colleagues at Ulstein, who made my time there enjoyable and helped me improve my foosball skills considerably.

Lastly, I dedicate this report to my family and friends, whose encouragement and belief in my abilities have been a constant source of strength.

I hope that this work contributes meaningfully to the ongoing efforts to make Ulstein's designs more sustainable, aligning with global goals for decarbonization and circularity.

Jochem Schuitemaker
Delft, November 2024

Summary

Summary

In 2018, greenhouse gas (GHG) emissions from shipping were estimated to account for 2.9% of global emissions, with projections indicating an increase of up to 44% by 2050 under various long-term energy and economic scenarios. In response, the International Maritime Organization (IMO) has set ambitious targets to reduce carbon intensity by at least 40% by 2030 and achieve net-zero GHG emissions around 2050.

This research explores the potential and implications of integrating life cycle environmental performance evaluations into early-stage ship design, moving beyond the traditional “tank-to-wake” focus to encompass the entire life cycle of a vessel. Incorporating Life Cycle Assessments (LCA) into the design stage promises to optimize vessel design by addressing environmental and economic impacts across its full lifecycle, from construction to decommissioning.

The primary objective of this report is to investigate the extent to which life cycle assessment optimization, based on cost and environmental impact, can be performed and implemented in the conceptual ship design of complex vessels, and to assess how it can support the development of new designs.

This study presents an analysis of the lifecycle stages of ships and introduces Ulstein Design & Solutions B.V.’s innovative design tool, *Blended*. Through an extensive review of life cycle thinking methods, material and energy flow analyses, industrial ecology practices, and socio-economic impact assessments, the research establishes criteria for evaluating the applicability of these methodologies. A trade-off analysis guides the selection of an appropriate approach, leading to the development of a novel method to integrate life cycle assessments into the *Blended* Design tool.

Key outcomes of the research include the identification of relevant life cycle assessment methodologies and their applicability to early-stage ship design. Additionally, an approach has been developed to integrate both cost- and GHG-emissions-based life cycle assessments into *Blended*, focusing on the shipbuilding and decommissioning phases. Furthermore, the study demonstrates how life cycle assessment integration can influence early design decisions, particularly by addressing the environmental and economic trade-offs that arise during construction and maintenance.

The study emphasizes the importance of addressing lifecycle impacts in early-stage ship design to prevent burden shifting between lifecycle phases. It also highlights the need for robust data collection and the development of performance indicators tailored to specific ship designs to enable reliable assessments, despite the limited information available at the early stages of design.

In conclusion, this research advances the understanding of how LCA can be applied in conceptual ship design to meet sustainability objectives. By enabling full lifecycle optimization within the *Blended* Design tool, it offers a pathway to creating vessel designs that balance environmental responsibility with economic viability, contributing to the maritime industry’s efforts to meet international decarbonization targets.

Contents

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Nomenclature

Abbreviations

Abbreviation	Definition
BC	Block Coefficient
BOF	Basic Oxygen Furnace
C2C	Cradle to Cradle
CapSEM	Capacity for Sustainable Energy and Material
CBA	Cost Benefit Analysis
CEAP	Circular Economy Action Plan
CFP	Carbon Footprint of a Product
CH_4	Methane
CML	Centre of Environmental Science Leiden
$COLCA_2$	Life Cycle CO2 Emissions
DALY	Disability Adjusted Life Years
DfE	Design for Environment
DP	Dynamic Positioning
EAF	Electric Arc Furnace
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EPD	Environmental Product Declaration
EU ETS	EU Emission Trading Scheme
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HTV	Heavy Transport Vessel
IEA	International Energy Agency
IHM	Inventory of Hazardous Materials
IMO	International Maritime Organization
ISA	International Standard Atmosphere
ISO 14040	Standard for LCA Framework
ISO 14044	Standard for LCA Requirements
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LCC	Life Cycle Costing
LCT	Life Cycle Thinking
LCSA	Life Cycle Sustainability Assessment
LCPA	Life Cycle Performance Assessment
MCI	Material Circularity Indicator
MCA	Multi Criteria Analysis
MEPC	Marine Environment Protection Committee
MFA	Material Flow Analysis
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
ReCiPe	Method for Environmental Impact Assessment
ROI	Return on Investment

Abbreviation	Definition
SEEMP	Ship Energy Efficiency Management Plan
SRI	Subsea Rock Installation
TCO	Total Cost of Ownership
UDSBV	Ulstein Design and Solutions B.V.
ULSTEIN HX121	Heavy Transport Vessel model by Ulstein Design & Solutions B.V.
WTIV	Wind Turbine Installation Vessel
WtW	Well-to-Wake
ZNE	Zero Net Emissions

Symbols

Symbol	Definition	Unit
A	Area	[m^2]
a	Mission-adjusted operational weighting factor	[dimensionless]
b	Weighting factor for lifecycle emissions	[dimensionless]
B	Beam of vessel	[m]
$C_{material}$	Carbon intensity of material production	[kg CO2/unit]
C_{O2}	Carbon intensity for various operations	[kg CO2/unit]
C_{steel}	Carbon intensity of steel	[kg CO2/tonne steel]
C_{CH4}	Emission contribution from methane	[kg CO2eq]
C_{N2O}	Emission contribution from nitrous oxide	[kg CO2eq]
$Capacity \times TotalDistance$	Normalization factor for emissions	[dimensionless]
$COLCA_2$	Lifecycle CO2 excluding operational emissions	[kg CO2]
D	Depth of vessel	[m]
DWT	Deadweight tonnage	[tonnes]
E_{CO2}	Emission of CO2	[tonnes]
$EEDIAE$	Emission from Auxiliary Engines	[g CO2/tonne-mile]
$EEDI_{LCA}$	Energy Efficiency Design Index adjusted for LCA	[g CO2/tonne-mile]
$EEDIME$	Emission from Main Engine power	[g CO2/tonne-mile]
$EEDIPTI$	Power take-in contribution	[g CO2/tonne-mile]
$EngineLoad$	Load factor during different vessel operations	[dimensionless]
$F_{maintenance}$	Maintenance frequency	[times/year]
GWP_{100}	100-year Global Warming Potential	[kg CO2eq]
L	Length of vessel	[m]
$L_{service}$	Service life of vessel	[years]
L/B	Length-to-Breadth Ratio	[dimensionless]
M	Mass	[kg]
NM	Nautical mile	[NM]
P	Power	[kW]
P_{inst}	Total installed power	[kW]
t	Time	[s]
$TotalDistance$	Total operational distance	[NM]
V	Velocity	[m/s]
V_s	Sailing speed	[knots]
W_{phase}	Weighting factor for lifecycle phase emissions	[dimensionless]
C_B	Block Coefficient	[dimensionless]

Symbol	Definition	Unit
η	Efficiency	[%]
ρ	Density	[kg/m^3]
ε	Emission factor	[g CO2/kWh]
ZNE	Zero Net Emissions target	[dimensionless]

1

Introduction and background

In 2018, greenhouse emissions from shipping were estimated to be 2.9% of global greenhouse gas emissions [2]. Emissions are projected to increase between 2018 and 2050 with up to 44% for a range of possible long-term energy and economic scenarios. In this context, the IMO has set a target to reduce carbon intensity by at least 40% by 2030 and to reach net-zero GHG emissions by around 2050 [2][3].

In recent years, more and more companies seek to adopt environmentally responsible practices, as a result from the IMO target and other voluntary and regulatory initiatives [4]. Besides lowering the impact on climate change, this can boost company reputations and brands. This, in turn, can make a company more attractive to investors, create stronger consumer loyalty, and enhance employee engagement, as leading consultancy firms acknowledge [5][6]. Simultaneously, these practices could contribute to substantial cost savings by improving products and processes and reducing waste.

Beyond the traditional narrowed focus on only the *"tank-to-wake"* operational performance of a product, several theories exist that include the full environmental or economic impact of a product over its life cycle. This life cycle includes the complete life of the product, from design, the extraction of raw materials for construction, to operation, maintenance and end of life. This research aims to explore the potential and effects of incorporating life cycle environmental performance evaluation into early-stage ship design. This chapter introduces the topic, provides background information, and outlines the research gaps and scope.

1.1. A life cycle perspective

In March 2020, the European Commission adopted the Circular Economy Action Plan (CEAP) [7], as part of the European Green Deal. The latest action plan introduces initiatives spanning the entire product life cycle, focusing on product design, promoting circular economy practices, advocating for sustainable consumption, and striving to minimize waste while maximizing the retention of resources within the EU economy [7]. A typical product life cycle diagram can be seen in figure 1.2.

In the CEAP, 35 actions are identified and determined that need to be taken on the pathway to net Zero in 2050 and beyond. To achieve this objective, the EU expresses the need for a shift towards a regenerative growth model that replenishes the planet, progresses towards maintaining resource consumption within planetary limits, and consequently at the same time to decrease its consumption [8]. The interrelation between a low environmental footprint and circularity is an important aspect of this plan. As, generally speaking, GHG-emissions are related to the production and life cycle of the raw materials used, obtaining greater material efficiency in for example the construction sector is claimed to be able to reduce total emissions (of that sector) with 80%[9]. As usually a lower GHG-emissions are attributed to reused or recycled materials compared to not-recycled materials, circularity would be a consequence of improving this material efficiency and designing for lower life cycle impacts.

As response of requests by the G7, the UN Environment Program International Resource Panel produced a report[10] in 2020 focusing on the greenhouse gas emissions reduction associated with resource efficiency. Between 1995 and 2015, the share of material production in the total GHG-emissions went up, with iron, steel and other metals being responsible for the biggest share of material emissions [10]. Although the report focuses on construction and light vehicle manufacturing, the report indicates that modifications in the design, building, upkeep, and dismantling of structures have the potential to diminish the quantity or carbon footprint of construction materials needed, lower energy consumption throughout a building's life cycle, prolong the lifespan of a structure, and facilitate the reuse or recycling of materials and components, thereby eliminating the necessity for new materials or components and attributed environmental impact [10]. Thinking about life cycle evaluation aligns with the United Nations' Sustainable Development Goals seen in figure 1.1[11]. The SDGs represent a pressing global mandate for all nations to strive towards achieving 17 goals by 2030, aiming to enhance economic, environmental, and social conditions for millions worldwide [12].

(a) SDG 12: Ensure sustainable consumption and production patterns

(b) SDG 13: Take urgent action to combat climate change and its impacts

Figure 1.1: Life cycle evaluation aligns with the United Nations' Sustainable Development Goals, retrieved from sdgs.un.org[12]

1.1.1. Maritime domain

The International Maritime Organization (IMO) introduced different approaches aimed at improving the environmental performance of maritime transport. Examples of this are the Energy Efficiency Design Index (EEDI) or the Ship Energy Efficiency Management Plan (SEEMP) [13]. These eco-labels consider only the operational phase of the life cycle, which results in the potential risk of 'burden shifting' the environmental (or economic) impact of the considered life cycle phase to other disregarded phases of the vessels life cycle[14]. A complete life cycle approach focusing on environmental and economic concerns would prevent this, and would lead to a comprehensive evaluation of the vessel performance [14]. One initiative involves creating a comprehensive product passport that documents all materials used during construction. This measure aims to enhance end-of-life disposal and recycling processes[15].

There are different drivers behind focusing on full vessel life cycle perspectives. This could involve determining the quantitative environmental and cost effects of an existing vessel or a vessel yet to be constructed. In both cases, the motivation for the analysis could be different. Firstly, a product with a lower environmental impact is to be designed to align with regulations and voluntary sustainability goals on GHG emissions. Furthermore, this approach could lead to a more comprehensive assessment of sustainable performance, a necessary step on the pathway to more sustainable and circular design. Ultimately, implementing life cycle analysis methods would ideally lead to vessel designs with better operational performance and lower costs. The Organisation for Economic Co-operation and Development (OECD) suggests including life cycle impacts during ship design to ensure clarity on how design decisions affect the environmental footprint of ships[16].

1.1.2. Approaches

In the recent years, Life Cycle Thinking (LCT) got the most attention when it comes to life cycle approaches, although implementation methods are largely unclear and not evaluated[17]. Life cycle thinking serves as a basis to advance the sustainability agenda in both the public and private sectors, aiding decision-making for a wide range of policy formulation, product development, production, procurement, and ultimate disposal. Within Life Cycle Thinking, various types of assessments, such as environmental, economic, and social assessments, can be conducted [17]. As LCT is currently mostly used on existing products, little is known on how it could support radically new designs [18]. Besides, it is mostly unclear how the future development of the environmental impact of the product is, which

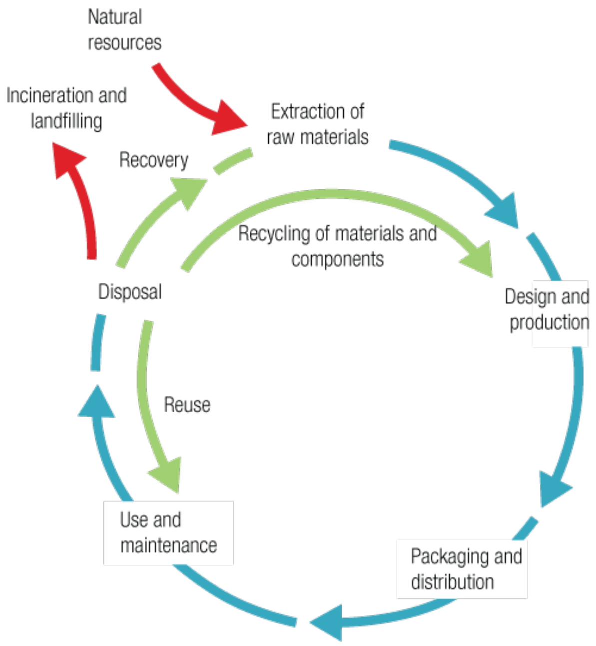


Figure 1.2: A typical product life cycle, retrieved from lifecycleinitiative.org[17]

is especially relevant considering ships where the materialization of the design could be years after conception.

Other concepts used include cradle-to-cradle (C2C) design [19], focusing mainly on recyclability and reusability aiming to create a closed-loop system. Based on this theory, certificates and scores can be awarded to products, outlining their sustainability performance. C2C also focuses on the related economic impact of products. Various other methods have been developed, and different names have been given to the process of environmental and cost analysis over a product life cycle. Examples include Design for Environment (DfE) and Total Cost of Ownership (TCO).

In the context of Life Cycle thinking, one can emphasize both environmental and cost considerations. Life Cyle Assessment(LCA) provides insights in sustainability of a product. Being an internationally standardized method, it is becoming the preferred way for companies to report on their environmental responsibilities. According to ISO 14040 and ISO 14044, a LCA is done in four stages: goal and scope definition(1), life cycle inventory analysis (LCI)(2), life cycle impact assessment (LCIA)(3), and interpretation(4) [20]. Performing LCA studies helps preventing lowering the environmental impact of one aspect of a product by increasing the impact of another aspect. LCA methods have been used on quantifying the environmental impact of existing maritime transport and operations[14].

Life Cycle Costing (LCC) analyzes the complete economic impact of a product throughout its entire life cycle. This extends beyond the raw material costs to include expenses made during operational lifetime and end-of-life disposal. In contrast to Life Cycle Assessment (LCA), the method lacks international standardization. Additionally, LCC may incorporate external costs, following principles like the ’polluter pays’ concept[21].

1.2. Circular economy in relation to life cycle assessments

While Life Cycle Assessment aids in assessing environmental or social impacts of product or service systems, it doesn’t inherently indicate the level of circularity in a solution. This gap is addressed by circularity indicators, which complement life cycle sustainability assessments by measuring the circularity of resources and material flows in studies.

When addressing circularity, different R’s often refer to the principles of the circular economy. These include Reduce: Minimizing waste and resource use, Reuse: Extending the lifespan of products by reusing them in their original form, Recycle: Reprocessing materials to create new products or ma-

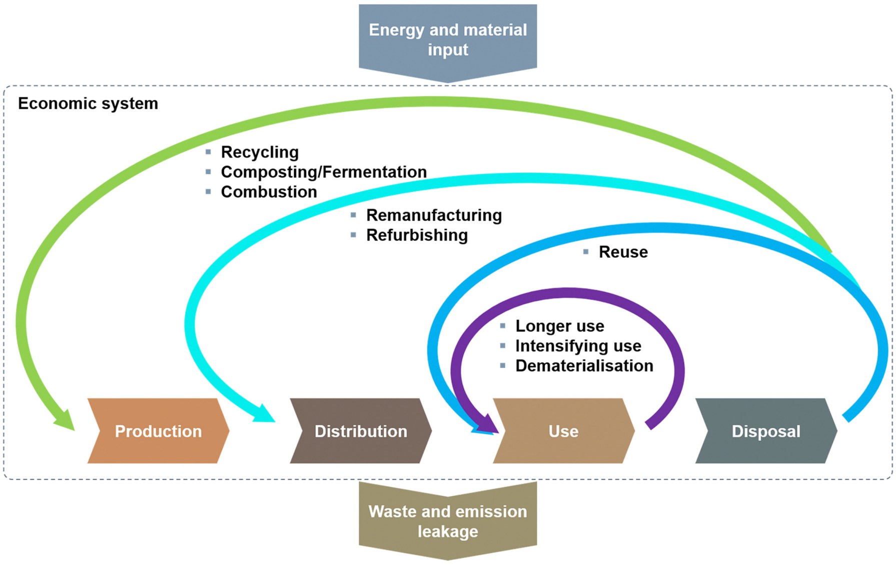


Figure 1.3: The circular economy, retrieved from Geissdoerfer et al. (2021) [26]

terials, Repair: Fixing products to prolong their usability, Refurbish: Restoring products to a like-new condition, Remanufacture: Rebuilding products to their original specifications, Rethink: Rethinking product design and consumption patterns to minimize waste and maximize efficiency. Different circular design approaches exist, some are broad in scope, such as design for disassembly, design for multiple life cycles, and design for longevity [22]. Others are more specialized, focusing on specific ”R” strategies, like remanufacturing [23]. In the review done by Stölze et al. (2023) [24] no method aiming at the early phases of circular product development was found. The circular economy concept is visualized in figure 1.3.

Despite the widespread recognition of circular economy principles as vital for economic, environmental, and social sustainability, no clear standards and guidelines for implementing circularity in shipbuilding and operations exist. Using life cycle assessment methods, however, presents a promising pathway to overcome this challenge and establish effective frameworks for circular practices within the sector. Implementation of circular economy into shipbuilding would also include establishing links between circular indicators and LCA [25]. This relationship is not always clear, and defining relationships differently would lead to different results. Material Circularity Indicators (MCI), which indicate material quantity and linear or restorative flows of the material are able to add a circular economy perspective to a LCA. From this perspective, LCA would be a necessary stepping stone for achieving a circular economy.

Lonca et al. (2018)[27] showed that MCI and LCA assessment could lead to different results, where different scopes could be limiting. Solely prioritizing material circularity may not always result in the lowest environmental impact, as factors such as the life cycle of materials and the efficiency of product reuse can vary. In some cases, less circular materials might actually yield a lower environmental footprint over their life cycle. This is demonstrated, for example, in the case of car tires as shown by the author. Other authors, like Rigamonti et al. (2021) [28], also address the need of a combination of LCA tools and circularity to get a good assessment of sustainability and circularity. A multi-criteria method enables the assessment of various indicators, leading to a comprehensive understanding of the environmental impact caused by a product. A life cycle sustainability assessment would be integral to this approach.

1.2.1. Regulatory background

When it comes to ship recycling, both the IMO Hong Kong Convention and EU Ship Recycling Regulation address the environmentally conscious and safe recycling. The establishment and maintenance of an Inventory of Hazardous Materials (IHM) is mandatory. This inventory records various hazardous substances present in a ship’s structures and components. It accompanies the ship throughout its life cycle, from construction to recycling, ensuring thorough traceability and accountability. As these regulations were adopted at times circularity was less widely discussed, they fail to include design for recycling or the life of materials after the being used on a ship [29]. Despite this, these regulations are regarded as a crucial step towards fostering environmentally conscious ship recycling, collaboration throughout the ship's life cycle, and circularity. In the sustainable blue economy agenda outlined in 2021 by the European Commission [30] "work to mitigate the impacts on oceans and coasts to build a resilient economy model based on innovation, a circular economy and a respectful attitude to the ocean" is visioned and incentives for companies "that use or generate renewable resources, preserve marine ecosystems, reduce pollution and increase resilience to climate change" are addressed.

Conclusion on circularity

Integrating circularity into early-stage design tools presents a logical progression beyond the scope of Life Cycle Assessment. While LCA offers valuable insights into the environmental impacts of products and processes, circularity complements this by focusing on the entire life cycle of a product, including its design, materials, and end-of-life considerations. By incorporating circularity principles into design tools, such as considering material reuse, recycling potential, and product disassembly, further optimization of a design could take place in the fields of resource efficiency, minimal waste generation, and product lifespan. The impact of circular design on company business models is not extensively researched, thus raising questions about its economic viability and if designing for more circularity would be pursued from a financial standpoint. Within LCA, adding circularity indicators could also be considered. Initiating LCA implementation in the design tool is a logical and essential starting point. Subsequently incorporating circularity could further enhance sustainability efforts and promote comprehensive eco-conscious design practices once LCA impacts are known.

1.3. Ulstein Design and Solutions B.V.

Ulstein Design and Solutions B.V. (UDSBV) is a naval architecture office in Rotterdam, the Netherlands. *UDSBV* develops novel full-custom ships for the offshore wind, oil and gas industries, with a speciality in heavy lift crane vessels, pipelay vessels/barges, rock installation vessels, wind farm installation vessels, shallow draught construction support vessels, and drill ships [31]. An example of a heavy transport vessel designed by *UDSBV* can be found in figure 5.2, this vessel was used by Peeten (2022) during his graduation research [32]. *UDSBV* provides concept and basic design studies, as well as engineering consultancy and salvage support for clients worldwide[31]. The company specializes in concept development, SPS compliance, (damage) stability, vessel motions, and structural integration, with supplementary offerings such as wind tunnel testing, inclining tests, docking calculations, and fuel optimization studies [31].

Figure 1.4: ULSTEIN HX121, retrieved from Ulstein.com [33]

1.3.1. Blended Design

Blended Design, was developed by Zwaginga et al. (2021) [34] for *UDSBV* to assist their Naval Architects during the concept design phase of vessels yet to be designed. *Blended Design* is a method that facilitates the concurrent development of the business case and the initial vessel concept by ship designers and their clients. It is implemented as software tool capable of generating various versions of a concept for a complex offshore vessel type. *Blended Design* aims to identify the optimal design solution considering both cost and greenhouse gas (GHG) emissions over the operational life of the vessel [32]. The design, identified as the champion, is presumed to be the most profitable. *Blended Design* will be further discussed in chapter 2.

1.4. Towards Holistic and Sustainable Ship Design

Thus, as the maritime industry moves toward sustainable development, integrating life cycle assessment and circular economy principles in ship design becomes increasingly essential. While various methods and tools have emerged, including LCA, Life Cycle Costing (LCC), and circularity indicators, significant gaps remain in their application to the design phase of maritime vessels. Current industry practices often overlook these holistic approaches, focusing predominantly on the operational phase and risking burden shifts across the life cycle. To meet ambitious international goals, such as those set by the IMO and the EU Circular Economy Action Plan, it is crucial to bridge these gaps by exploring how early-stage design can incorporate life cycle thinking and circularity. This chapter now identifies specific research gaps that this study aims to address in enhancing sustainable ship design practices.

1.4.1. Research Gaps

At first glance, different research gaps can be identified from literature, these can be divided in the three different categories.

Detailed environmental assessments of existing (cargo) vessels are slowly becoming more frequently performed. However, **the impact of applying a full life cycle assessment concept in the design phase of vessels, in general, is unknown** [35]. Research is needed to explore the successful integration of cradle-to-cradle life cycle analysis into ship design methods, aiming for optimal sustainability and cost efficiency in early-stage design. Although this upfront execution of the assessments has been identified as promising, it appears not to be attempted in practice and evaluated. Finding effective ways to achieve this would be highly useful for designing vessels that are both more sustainable and cost-effective [14]. The most relevant method or theory for life cycle assessment needs to be determined in order to perform this integration in the design phase. Whether Life Cycle Thinking is the preferred concept in this context, has to be seen. Besides, the lack of a standardized cost based life cycle concept raises questions about the best practices for its effective implementation.

Secondly, in order to successfully develop a method for performing a life cycle assessment, **several procedures need to be established that go beyond standardized procedures** as these lack a detailed approach needed to perform a full assessment[11]. As part of this, specific performance indicators within these assessments related to specific ships need to be developed, both for cost based and sustainability based evaluations. The development of these performance indicators is crucial to come to the best optimization of the design. Ultimately, the method including the performance indicators would enable the observation and evaluation of how different early stage design choices would be made based on one or different theories. Considering the constrained information available at this design stage and the significant influence of the high-impact decisions made during this phase, the design choices made during the early-stage design hold particular importance. Finding this method to conduct reliable assessments of a multitude of potential vessel designs poses the biggest challenge, given the constraints of available information during this phase.

Thirdly, considering the complexity of ship systems, **there is a need to find an efficient way to collect adequate data regarding the environmental and cost impact of materials used for the construction of the design and associated processes in ship building and decommissioning**[35]. Data collection is integral to the accuracy, reliability, and usefulness of Life Cycle Assessment. It ensures that the assessment reflects the real-world impacts of a product or process. Where data lacks, or the detail level of the conceptual design is not high enough, methods need to be found that could make accurate estimations needed to effectively perform the assessments. Several theoretical frameworks exist within different life cycle assessment theories, but the applicability and accuracy in (early stage) ship design should be further explored. The effects of uncertainties and variations from regional factors during construction and decommissioning in this context has not been researched. Investigating these aspects becomes particularly intriguing when considering specific vessel types, such as complex offshore vessels operating globally. Besides, more research needs to be done to see how the data could reflect durability and long-term performance of design.

In conclusion, addressing the identified research gaps, the objective is to develop a robust method and tool for conducting life cycle sustainability assessments during the early design stages of offshore vessels. The developed tool will implement procedures tailored specifically for life cycle assessment in offshore vessels and streamline data processing. Furthermore, the aim is to integrate these assessments into *UDSBV*'s *Blended Design*. This integration will allow for a comprehensive analysis of design consequences in *Blended Design* and facilitate a comparison of early-stage design outcomes with and without the implementation of a life cycle sustainability assessment. This integration will not only enable more efficient and competitive *UDSBV* designs but primarily contribute to reducing their environmental impacts.

1.4.2. Research Objective

The objective of this thesis is to investigate the potential of taking into account full life cycle assessments, both cost-based and sustainability-based, in early design stages of complex vessels. A new approach will be developed, targeting successful implementation of life cycle sustainability assessments into the early-stage ship design tool *Blended Design*.

Finding ways to perform assessments like LCA and LCC for ship design applications in *Blended Design* would enable for a full life cycle optimization of the designs, potentially leading to better designs. Besides, a design stage life cycle assessment would provide clients with valuable and more complete information about the design's full life cycle.
As Blended already includes a module accounting for the environmental impact during the operational lifetime of the vessel, the primary focus of research will be on shipbuilding and decommissioning.

The aim of the thesis is to answer the following research question:

"To what extent can life cycle assessment optimization, based on cost and environmental impact, be performed and implemented in conceptual ship design of complex vessels?"

This will be done by answering different sub-questions. The first of these sub-questions will be answered in chapter 3, after which an approach will be proposed. Chapters 2, 3, and 4 will serve as the foundation for developing a new approach in order to be able to provide answers to the remaining research questions in subsequent phases of the research. The sub-questions are as follows:

1. *What life cycle assessment concepts and methods exist and to what extent are they relevant for ship design?*
2. *How can cost- and GHG-emissions-based life cycle assessments be reliably performed and used in the early-stage design of complex, globally operating vessels?*
3. *How can Blended Design be expanded to include a full life cycle assessment, including cost and GHG emissions in the ship building and decommissioning?*
4. *How would a full life cycle optimization in Blended Design perform and lead to different choices in early stage vessel design?*
5. *What is the impact of ship building and decommissioning on GHG-emissions based life cycle assessment outcomes?*
6. *What is the impact of ship building and decommissioning on cost based life cycle assessment outcomes?*

Scope

A defined scope is essential for both life cycle assessments and the study of their effects on vessel design. The research will focus on vessels in the market where Ulstein Design and Solutions B.V. operates: complex full custom vessels used in the offshore industry. The life cycle assessment will be tested on an existing vessel concept, e.g. HTV HX121, which was also used as case study in the research by Peeten (2022) [32]. As environmental impact and operational costs during the operational life are already included in *Blended Design*, the research will focus on conducting a life cycle assessment for environmental and economic impacts of the excluded components within the vessel life cycle. This implies that the development of the life cycle analysis method will primarily concentrate on the non-operational life of the vessel, considering the associated environmental footprint and costs. Given the higher relevance of GHG-emissions, the research will exclusively focus on GHG emissions in the environmental assessment, while other harmful emissions or environmental impacts will be excluded from the scope. The new approach will not include circular thinking.

2

Maritime lifecycle environmental impact: a ship designer's perspective

In order to address the main research question *'To what extent can life cycle assessment optimization, based on cost and environmental impact, be performed and implemented in conceptual ship design of complex vessels?'* and the first sub-question *'What life cycle assessment concepts and methods exist and to what extent are they relevant for ship design?'* as where defined earlier, this chapter will establish a framework for evaluating the applicability of life cycle assessment concepts and methods in ship design. This exploration involves examining various vessel lifecycle phases and introducing the innovative *Blended Design* tool developed by *UDSBV*, which integrates diverse design aspects to optimize concept designs. By synthesizing insights from these lifecycle stages and the *Blended Design* approach, the chapter aims to define criteria that will guide subsequent analyses, ultimately laying the groundwork for answering the first sub-question in the subsequent chapter.

2.1. Maritime lifecycle emissions

Before finding an approach for lifecycle impact assessments, an understanding of different lifecycle phases of ships needs to be obtained. Different phases in the lifecycle of a ship can be identified, as is shown in figure 2.1. In this section processes occurring during different lifecycle stages will be further described.

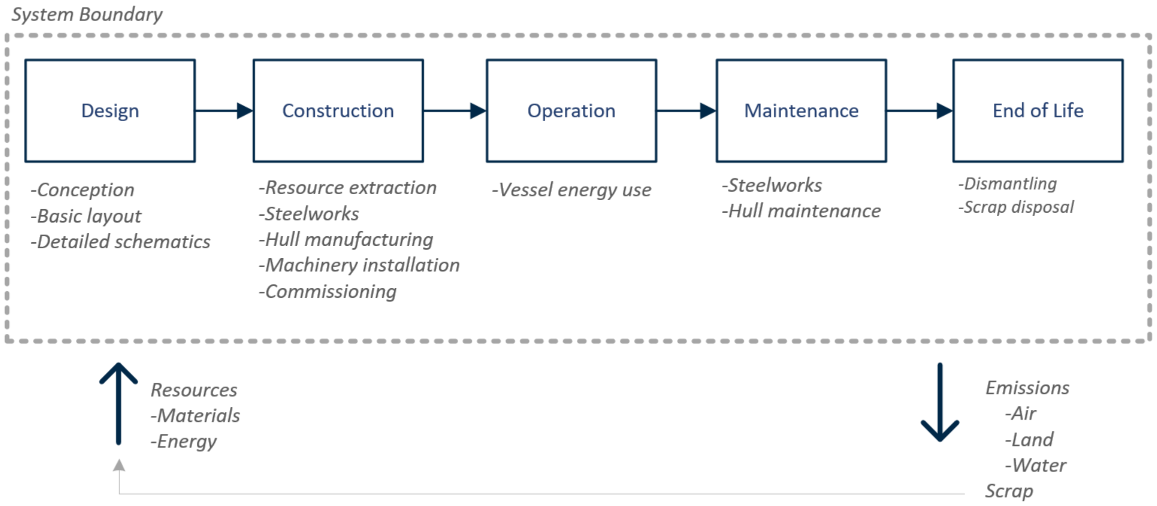


Figure 2.1: Main phases in a vessels lifecycle, based on Mondello et al. (2020)[14]

2.1.1. Design

The design stage marks the inception of a vessel's lifecycle, where the initial blueprint of the ship takes shape. It includes the conception, basic layout, and detailed schematics of the vessel. Engineers, naval architects, and designers collaborate closely with the client, considering various factors such as intended use, size, propulsion, and safety regulations. This phase is crucial as it lays the foundation for the entire construction process, ensuring that the final product meets operational requirements, safety standards, and efficiency goals. From conceptual sketches to detailed technical drawings, the design stage sets the course for the ship's journey from conception to construction.

Within the design stage, specific decisions relevant to the ships life cycle impact are made. These include the selection of materials, size, machinery, vessel speed which all greatly influence the vessel performance, profitability and environmental impact.

2.1.2. Construction

In the construction stage of shipbuilding, a series of critical processes unfolds, each playing an important role in shaping the final vessel. From the extraction, production and processing of raw materials to the hull manufacturing and installation of machinery, every step is integral to the creation of a seaworthy vessel. During the construction, a wide array of logistical processes takes place. This section delves into these diverse processes, providing a compact overview that serves as the foundation for understanding different processes in ship manufacturing relevant for a ship sustainability assessment.

Raw material extraction, production and processing and transport

Steel is the main material used for the production of ships. Earlier research showed that extraction and raw material production of steel could account for 95% of the vessel's manufacturing related impacts [36]. On a global scale, steel accounts for approximately 25% of industrial CO_2 emissions[37]. There are two routes to manufacture steel: the use of Basic Oxygen Furnace (BOF) and the recycling of scrap via an Electric Arc Furnace (EAF), the BOF also requires up to 30% scrap steel [38]. According to World Steel (2021)[39] nearly 90% of BOF are coal-powered, whereas EAF are predominantly powered by electricity, primarily sourced from national grids by a variety of sources.

Scrapping and recycling are pivotal in material transfer across various markets, with recent studies indicating that steel recovery rates currently stand at around 95% , this recovered steel has a lower environmental impact compared to newly furnaced steel [40]. Different steel manufacturers target a significant reduction in steel production related emissions, aiming for a carbon intensity reduction of steel production of 50% by 2050 [15]. In other words, steel production will still have a significant environmental impact in 2050. Besides, it should be noted that scrap steel availability is projected to be 900 Mt a year by 2050, whereas current demand is approximately 1800 Mt a year[38]. In 2050, 60% of steel demand is projected to be provided by coal or gas powered BOF production, possibly combined with carbon capture processes[41]. Hot rolled steel accounts for 80% of steel used in the shipbuilding industry [42]. Both BOF and EAF steel can be utilized in shipbuilding, provided that quality standards are met. However, due to concerns regarding quality, BOF steel is primarily favored in ship construction. In general, producing high-quality steel suitable for ship construction necessitates equally high-quality scrap steel as a source, which availability cannot always be guaranteed [43].

Hull manufacturing

The hull manufacturing stage in shipbuilding involves a series of intricate processes essential for constructing the vessel's foundation. Cutting and welding are the initial steps, where steel plates are precisely shaped and joined together to form the hull's structure. All throughout the hull manufacturing stage a flow of materials is transported towards the shipyard. Sandblasting is employed to remove any surface contaminants and prepare the hull for coating, enhancing its durability and resistance to corrosion. Coating applications protect the hull from harsh marine environments, while anodes prevent corrosion by attracting corrosive elements away from the ship's surface. Outfitting completes the hull manufacturing stage, incorporating essential systems, equipment, and furnishings to ready the vessel for operation. In a study by Quang et al. (2020)[44], it is assumed that 10% of the construction weight of steel is lost in cutting processes during the hull manufacturing phase.

Machinery installation

Onboard a ship, a diverse range of machinery is essential for its operation and functionality. This includes propulsion systems such as engines, turbines, or propellers, which provide the necessary power for propulsion and maneuvering. Additionally, auxiliary machinery like generators, pumps, and compressors support various onboard systems, including electrical power generation, water supply, and air conditioning. Navigation equipment such as radar, GPS, and gyrocompasses ensures safe and accurate navigation, while communication systems enable connectivity with other vessels and shore facilities. Additionally, cargo-handling machinery such as cranes, winches, and conveyor systems facilitates the loading and unloading of cargo. Moreover, firefighting and safety equipment like fire pumps, extinguishers, and lifeboats are crucial for onboard safety and emergency response. The choice of machinery also has a significant impact on the environmental performance of the ship, largely as a result of the operational performance of the chosen machinery, as well as the environmental impact of machinery production.

An offshore equipment vessel requires a diverse array of specialized machinery to support its operations in challenging marine environments. This machinery typically includes heavy-duty cranes for lifting and maneuvering equipment, such as monopile foundations. Dynamic positioning systems ensure precise vessel positioning without the need for anchoring or jacking, crucial for conducting delicate operations in deep waters. Additionally, winches and towing equipment enable the vessel to tow and deploy various types of equipment and structures. Sophisticated navigation and communication systems are essential for safe navigation and coordination with offshore installations and support vessels. Furthermore, the vessel may be equipped with advanced machinery for handling and servicing subsea equipment. Overall, the machinery onboard an offshore equipment vessel plays a vital role in supporting offshore construction, maintenance, and other activities.

Other yard processes

Various yard processes play an important role in finishing the vessel. These include a range of activities essential for transforming raw materials into a seaworthy vessel. Among these processes are outfitting, where the ship's interior is fabricated and installed to accommodate crew and passengers, including the installation of furnishings, amenities, and safety equipment. Moreover, different logistical processes take place during the different manufacturing stages. Additionally, quality assurance procedures rigorously monitor and evaluate every aspect of construction to guarantee adherence to safety standards and design specifications. Through these yard processes, the shipyard transforms steel, equipment, and components into a finished product, ready to execute operation for which the ship was designed [15].

Eventually, production ends with a vessel ready for service. Hull and installed machinery add up to the light ship weight.

2.1.3. Operation

During operation, emissions are a result of the drive and energy systems onboard. CO_2, NO_x, SO_x, CO, PM, VOCs, methane (CH_4), black carbon (BC), and particulate organic matter (POM) constitute the most harmful exhaust emissions for to both human health and the environment, particularly attributing to global warming. Airborne pollutants from shipping operations are significantly influenced by factors such as fuel type, engine specifications, combustion efficiency, lubricating oil properties, operational conditions, vessel design, and equipment efficiency [45]. The operation phase of the vessel traditionally has the highest Global Warming Potential life cycle impact [44]. The CO_2 emissions during operations vary due to the influence of fouling. After maintenance, when fouling is removed, CO_2 emissions are lowest, increasing as fouling grows.

Fuel related life cycle emissions

The IMO reports on the projection of GHG emissions from maritime shipping focus up until this point on Tank-to-Wake emissions. These are the emissions as a result of the combustion of fuel on board during the operation. In the meantime, there is growing attention on Well-to-Tank emissions occurring in the energy supply chain for shipboard use, right up to when they are loaded onto ships. The FuelEU Maritime Regulation aims to establish targets for the yearly greenhouse gas intensity of shipboard energy use, encompassing CO_2, CH_4, and N_2O emissions from both Tank-to-Wake and Well-to-Tank phases. Guidelines for the Fuel Life Cycle GHG Analysis are also developed at IMO level [46]. The Marine Environment Protection Committee (MEPC) approved these guidelines concerning the life cycle greenhouse gas (GHG) intensity of marine fuels, in July 2023[47]. These guidelines facilitate a comprehensive assessment, from well to wake, including emission factors from production to utilization stages, to determine the overall GHG emissions associated with marine fuel. These guidelines include a formula for the calculation of the Tank-to-Wake GHG emissions with additional factors applied to permit adjustment of the CO_2 emission factor based on the carbon source (fossil, biogenic, or captured carbon) of the respective fuel[47].

The IMO has set 'indicative checkpoints' on the pathway towards net-zero, and the 2023 IMO Strategy suggests that these ambition levels and milestone markers should consider the well-to-wake greenhouse gas emissions of marine fuels, as outlined in the Organization's Lifecycle GHG Intensity Guidelines for Marine Fuels (LCA guidelines)[3]. The primary aim is to decrease GHG emissions within the framework of international shipping's energy system while preventing the burden shifting of the GHG emissions to other sectors.

2.1.4. Maintenance

During the maintenance stage in a vessel's lifecycle, scheduled inspections are conducted to ensure optimal performance and safety. These regular assessments focus on evaluating wear and tear of coatings, identifying any structural deficiencies, and assessing the overall condition of hull fouling. Maintenance tasks involve various activities such as welding repairs, thorough cleaning through techniques like sandblasting, applying protective coatings through painting, and ensuring effective anode protection to prevent corrosion. By addressing these aspects systematically, maintenance tasks aim to uphold the vessel's operational integrity and longevity. Activities during maintenance are by some regarded as the same as during the construction phase, only with different amounts of materials used [48]. In a study by [44], the amount of steel used during the complete lifecycle maintenance is assumed to be 10% of the steel used during construction.

Maintenance intervals influence the environmental performance of ships greatly, as removing fouling improves fuel economy during operation. Research by [49] finds that the considered interval time between hull cleaning and recoating has a significant effect lifecycle GWP impacts. Besides, for increased steel weight, hull maintenance could be reduced, resulting in lower lifecycle costs.

2.1.5. End of Life

At the End of Life of the vessel, either the hull of the vessel (if structurally still in good condition) can be reused in the construction of a new vessel. Otherwise, the vessel can be scrapped. During scrapping, the hull is broken into smaller parts which can be handled for recycling, typically resulting in part of the steel entering the local market of the scrapping area. Estimations done by Cooper and Allwood (2012) [50] state that 85% of steel and 10% of aluminum used in the vessel could be reused.

There are various methods for dismantling a vessel, whether it is beached, demolished alongside, on a slipway or in a drydock. Typically, cutters are employed to divide the vessel into smaller parts that can be reused or recycled. Scrapping locations for different Gross Tonnage (GT)'s are shown in figure 2.2. According to Bleischwitz et al. (2023) [51], less than 1% of vessels with a beneficial owner in the EU — so including vessels of EU companies sailing under non-EU flags — are scrapped inside the EU. Typically at the end of life, vessels are registered under a breaking flag and scrapped in locations as shown in figure 2.2. However, different initiatives are being developed promoting more sustainable ship recycling. The potential inclusion of steel in the emissions trading system would target the carbon emissions of steel, encouraging the recycling of steel. The Hong Kong Convention provides incentives for compliance with stricter recycling regulations, also mandating the consideration of ship recycling during design and construction of the vessel[51]. For most cases, this in the first place means having a detailed oversight of materials and liquids present in the ship which need to be taken into account during end of life. The convention is set to enter into force in 2025 [52]. Besides that, relevant industries set goals for achieving net-zero carbon emissions, increasing the need for scrap steel reuse in the value chain. Ships will play a significant role in providing this scrap steel.

After scrapping, steel can be rerolled and directly used or remolten. In India, plates are cut from the ship hulls which are rerolled and used mainly in the construction sector leading to a 90% reduction in environmental impact when furnacing of new steel is prevented [15][51]. In China and Türkiye, most of the scrap is remolten[15].

In earlier performed life cycle analysis of ships, the ship-recycling stage only accounts for a small percentage of total emissions, maximizing at 10% for the hull subsystem of ships. Waste composition can be classified in three categories, being treatable (ballast/bilge water), landfillable (heavy metals, glasswool), and incinerateble (wood, plastics etc.)[15]. Waste generation as percentage of ship weight is geographically different, and ranges from 1% in Bangladesh to 10% in Türkiye. The low percentage in Bangladesh is mainly due to the reuse of glasswool in the construction sector, as opposed to using it in landfill.

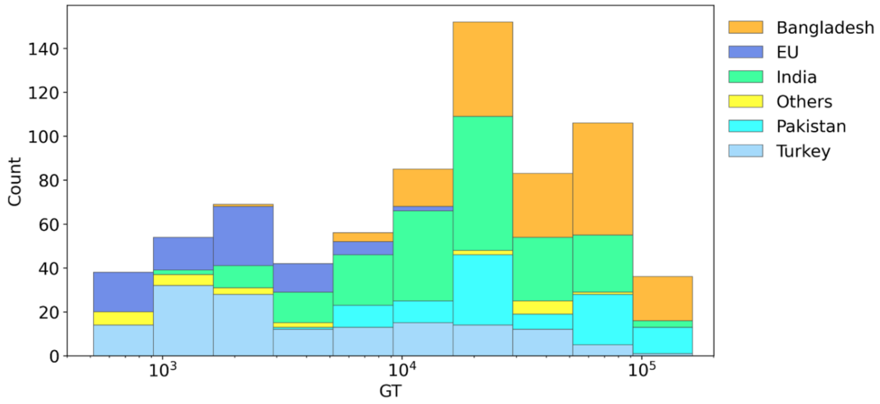


Figure 2.2: Numbers of scrapped ships from 2017 to 2022 in relation to their size in GT and their breaking location (colors). Retrieved from Bleischwitz et al. (2023)[51]

2.1.6. Known lifecycle impacts

Based on earlier performed detailed assessments of the lifecycle of existing ships, a first idea of the order of magnitude of the contribution of different lifecycle phases can be obtained. Within the maritime domain, different life cycle approaches have been used to assess the environmental impact of ships. For example, in 2020 a life cycle assessment focusing on GHG emissions of a Bulk Carrier was performed by Quang et al. (2020)[44] using a method developed at Leiden University. On a 1997 bulk carrier, running on HFO, the life cycle assessment suggests that more than 10% of CH4 emissions and around 5% of CO_2 and N_2O emissions result from the construction phase of the vessel, where material used has the highest impact. In a case of a Medium Range tanker vessel from 2008, the operational phase accounts for 79% of GHG emissions [53]. If it is considered that the steel is recycled after scrapping, the End of Life is attributed a negative emission impact [44]. Lingchin et al. (2016)[54] performed a study comparing the life cycle impact reduction of a new build vessel with an alternative energy systems, which could reduce lifecycle GHG impacts by 50%. For lower GHG emissions during operations, the environmental impact of vessel construction and scrapping is more significant on the total lifecycle. Similar conclusions can also be drawn from research by Wang et al. (2023)[55].

The question also arises as to what the best lifecycle duration for a vessel is and what the associated environmental impacts of the design are. Dong et al. (2018) [56] studied the lifecycle environmental impact of two vessel designs, one with a higher and one with a lower lightship weight, designed to have a 30 year and 20 year lifecycle duration respectively. The research concludes that a vessel with thicker steel plating, which is presumed to be more corrosion resistant and have a longer lifetime, has a smaller overall lifecycle environmental impact despite a higher lightship weight. However, no research has been done on the optimal lifetime for a vessel from an environmental impact point of view. The considered lifecycle length is also related to the economical lifetime of the vessel, which needs to be accounted for when analyzed.

2.2. Blended Design

This research is a continuation of the effort done during earlier research by Zwaginga (2021) [34], Peeten (2022) [32] and de Ridder (2023) [57] in cooperation with *UDSBV* to develop a design tool that co evolves ship design with a market model. *Blended* helps the ship designer to determine the general ship geometries with the best economical potential.

Blended Design was developed as a method to incorporate market uncertainty in early stage ship design by Zwaginga et al. (2021)[34]. The approach involves uncertainty modeling before the requirement definition phase through comprehensive global market research. Additionally, during the concept design stage, it iteratively refines both the vessel design and its business case concurrently. The tool is built using the programming language Python. During the concept phase, additional insights in the market and results from design iterations lead to new assumptions in the model. New design solutions can be reviewed using *Blended*. Three main components can be distinguished: a market simulation model, a ship model and an uncertainty model. The first two use supply and demand to generate relevant ship configurations base on the market anticipations. Evaluation and visualization is performed by the uncertainty model. Effectively, the model is capable of generating hundreds of thousands of unique ship configurations with varying dimensions, operating speeds and other varying (mission specific) specifications. Economical indicators of all configurations are assessed for different market scenarios. The design space can be limited by the designer, based on operability limits, port restrictions or limitations based on the mission the vessel has to perform. A graphical overview of *Blended* developed by Zwaginga et al. (2021) [34] can be found in figure 2.3.

Peeten (2022) [32] made efforts to extend the model with the possibilities to assess operational environmental performance of Heavy Transport Vessels (HTVs). In 2023, de Ridder [57] modularized the model and added new parts addressing seakeeping behavior an include wind turbine installation vessels in the design space.

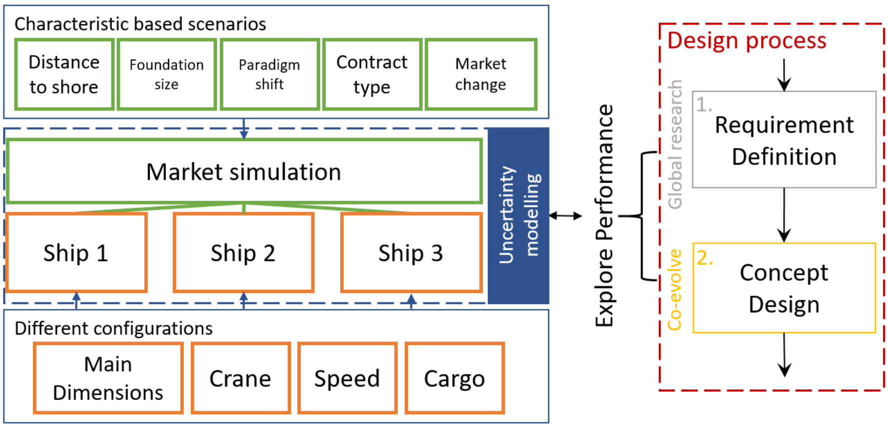


Figure 2.3: Representation of the working of *Blended* as developed by Zwaginga et al. (2021)[34]

2.2.1. Market Model

The market model is used to allow for a simulation of the market the vessel intends to operate in. For offshore wind related missions, market data from 4C offshore is used as basis for the modeling. From the database, more than 20 data points of all wind farms are used, validity of the data was confirmed in meetings with industry by Zwaginga[34]. Windfarm size data is extrapolated and market trends and forecasts are found. Market uncertainty is incorporated when setting the lower and upper bounds for windfarm size. The designers can adjust these boundaries based on their own insights and opinions.

Using a probability function designed to control the mean value and therefore account for unrealistic outliers in the dataset, a probability matrix was generated. This matrix contains cumulative probability data for various monopile diameters, for a chosen step size of 0.01m.

The market model focuses on monopile foundations, mass and dimensions. In 2022, Peeten [32] expanded the model with a database on alternative fuels, allowing for making forecasts on future alternative fuel prices.

2.2.2. Ship model

The ship model creates a wide range of realistic designs base on a reference model. The ship model consists of different modules, enabling individual verification and validation. These modules are Scaling (1), Weight Estimate (2), Power and Propulsion (3), Mission (4) and Cost and Income (5). For each design parameter a range of inputs is used. A program creates combinations of all possible values.

Theoretical and empirical validation is analyzed. Besides, a sensitivity analysis is performed for each module and for the complete model.

In the weight module, different weight groups are identified which are validated against reference vessels. These weight groups are: hull weight, main engine weight, crane weight, equipment for crew and passengers weight, machinery weight, common systems weight, sailing equipment (navigation and mooring) weight. In the research of Zwaginga et al. (2021)[34], the use of a database of reference vessels for weight estimations is seen as a good way for determining the weights of different groups. Due to the limited availability of vessels for regression analysis and the varied mission equipment tailored to individual client needs, finding correlation from reference vessels proves challenging. Therefore, scaling of a reference vessel is used in the model.

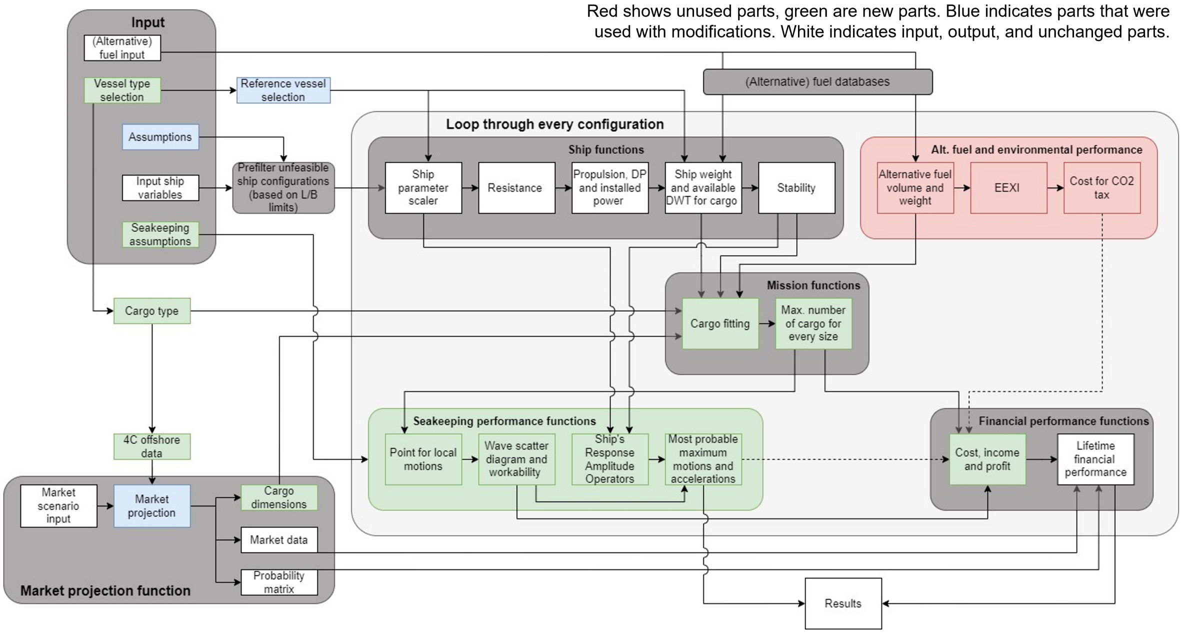
In 2022, alternative model was added by Peeten [32], allowing for the selection of alternative fuels. in 2023 de Ridder [57] added a seakeeping module, capable of calculating RAO and most probable motions and accelerations. Besides, efforts were done to modularize *Blended* in order to make it usable for different vessel and cargo types and corresponding missions.

2.2.3. Uncertainty model

On the intersection of the market model and the ship model, lies the mission model. By using the probability matrix from the market model, the probability a certain mono pile size is used in a certain year is known. By coupling this to the capacity of the vessel from the ship model the performance of the vessel in the market can be modeled. Using a measure of merit the performance of the vessel over its lifetime is assessed. The probability of profit is used to calculate the mean profit of the investment. A discounted Markov Chain with Rewards (MCR) with a finite horizon is used to calculate the ships value and earnings. Ultimately, the Return on Investment (ROI) of the design is found.

In 2022, the model was expanded with alternative fuels, including modules determining environmental performance with EEXI. Costs of fuels and technology are incorporated, as well as an implementation of a carbon tax. Together, this allows for a complete assessment of fuel and emission related financial implications for CAPEX, OPEX and VOYEX.

An overview of the different functions of *Blended*, as used in the research by de Ridder[57] can be found in figure 2.4.



Red shows unused parts, green are new parts. Blue indicates parts that were used with modifications. White indicates input, output, and unchanged parts.

Figure 2.4: Integration of functions in *Blended Design*, as used in research by [57]

Concluding Remarks

The use of *Blended* as a life cycle design tool currently encompasses various stages of the vessel lifecycle. The objective of the new approach is to enhance the tool by addressing its existing gaps, as illustrated in Figure 2.5. The life cycle stages which are not fully covered are marked with an 'x'. These identified gaps in *Blended*, alongside the previously discussed stages of a ship's lifecycle, provide a foundation for establishing criteria to guide the exploration and evaluation of life cycle assessment methods further.

	Design & Manufacturing	*Operation*	*Maintenance*	*End of Life*
Emissions	✗	✓	✗	✗
Costs	✓	✓	✓	✗

Figure 2.5: Lifecycle phase gaps in *Blended*

2.3. Criteria

Based on the lifecycle stages identified earlier in this chapter and insights gained from *Blended Design*, as well as research gaps related to life cycle perspectives in early stage ship design as mentioned in chapter 1, this section establishes the criteria that a new approach for offshore vessels must meet. These criteria serve as the basis for evaluating existing life cycle assessment frameworks and methods in literature, as well as facilitating the identification of the most promising approaches and components thereof.

1. **Ability to handle scarcity of data:** In the earliest stages of vessel design, only general sizes and power estimations are typically available, resulting in a low level of detail. Therefore, a critical aspect of developing a lifecycle sustainability assessment tool for offshore vessels is the ability to handle the scarcity of data inherent in these early design phases. Such a tool must employ estimation models capable of generating reliable estimates despite limited data availability. Remarkably, *Blended Design* already employs similar techniques, using estimation models to identify relevant ship sizes. Thus, integrating a lifecycle sustainability assessment component into *Blended Design* requires a method capable of effectively managing and leveraging scarce data to provide accurate environmental assessments.
2. **Mature method:** For implementation in *Blended*, a certain level of maturity of the method is desired. Utilizing a mature technology is crucial for establishing an approach that effectively addresses the main research questions. It ensures robust and consistent results, along with user-friendly guidelines or clear possibilities for real-life execution. Methods that are purely conceptual, lacking clarity on how a framework translates into a practical approach, pose a risk of yielding unreliable results. This potentially leads to ineffective outcomes in real-world scenarios. For this criterion, the level of mature is expressed in if a practical approach is clear or has been performed in the past.
3. **Reliable results:** Reliability is paramount when integrating a Life Cycle sustainability assessment method into an early stage design tool. It ensures that the environmental impact assessments produced are accurate and trustworthy, enabling informed decision-making from the outset of the design process. Designers and stakeholders must have confidence in the results to effectively guide sustainable design choices and mitigate environmental risks. Moreover, reliable LCA methods would further enable possible compliance with future regulatory requirements, which increasingly demand rigorous assessment and reduction of environmental impacts throughout a product's lifecycle. For all cases, an approach needs to be found capable of generating or estimating reliable results
4. **Approach to alternative scenarios:** Addressing different scenarios is crucial when integrating a Life Cycle Assessment method into an early stage design tool. This criterion ensures that the method can accommodate various design options, materials, and production processes, allowing designers to assess the environmental impacts across different scenarios. By considering multiple scenarios, designers can explore the environmental implications of different design choices and identify opportunities for improvement. A flexible approach to different scenarios enables

designers to account for uncertainties, such as changes in material availability, energy sources or manufacturing technologies, thereby enhancing the robustness and applicability of the environmental assessments. Additionally, considering diverse scenarios helps designers anticipate potential challenges and adapt their designs to minimize environmental impacts throughout the product lifecycle. Ultimately, a LCA method that can effectively address different scenarios would empower designers to make more informed and sustainable decisions early in the design process, leading to better environmental outcomes and increased resilience in product design and development.

5. **Regional variability:** This criterion acknowledges the diverse environmental conditions and regulatory frameworks across different regions where these vessels operate. By considering regional variability, the LCA method can capture location-specific factors such as weather patterns, water depths, and marine ecosystems, which significantly influence the environmental impacts of vessel operations. Moreover, regulatory requirements and infrastructure availability vary between regions, affecting the choice of materials, fuels, and waste management practices. An LCA method tailored to regional variability enables designers to account for these factors, optimizing vessel designs for specific operating environments while ensuring compliance with local regulations and minimizing environmental footprints. By addressing regional variability early in the design process, designers can identify opportunities to enhance the sustainability and resilience of offshore vessels, contributing to more environmentally responsible and operationally efficient marine transportation systems.
6. **Compatibility with *Blended*:** Ensuring compatibility with *Blended Design*, *UDSBV*'s tool developed to incorporate market uncertainty and iterative design refinement in early stage ship design, is crucial when integrating a Life Cycle assessment. *Blended Design* utilizes a Python-based framework to iteratively refine vessel design and business cases concurrently, incorporating insights from market research and design iterations. By integrating LCA into this framework, designers can evaluate the environmental performance of numerous ship configurations generated by *Blended Design*, considering varying dimensions, operating speeds, and mission-specific specifications. This integration enables designers to assess the environmental implications of design decisions alongside economic indicators, facilitating informed trade-offs between environmental sustainability and economic viability. Furthermore, extensions to the model, such as the assessment of operational environmental performance and the inclusion of new vessel types like wind turbine installation vessels, broaden the scope of LCA within *Blended Design*, enhancing its applicability to diverse marine transportation scenarios. Ultimately, compatibility with *Blended Design* allows designers to holistically evaluate the environmental and economic impacts of early stage ship designs, supporting the development of more sustainable and resilient vessels.
7. **Manage interrelationships:** Integrating the ability to manage interrelationships into a Life Cycle Assessment (LCA) method for early stage ship design is essential, especially when considering the complex and interconnected nature of environmental impacts in maritime operations. This criterion acknowledges the interdependencies between various aspects of ship design, operation, and environmental performance. By managing interrelationships, the LCA method can capture the dynamic interactions between design choices, operational parameters, and environmental outcomes. For example, the selection of propulsion systems may impact fuel efficiency, emissions, and operational costs, while vessel design features such as hull shape and weight distribution can affect performance metrics like stability, fuel consumption, and emissions. Additionally, considering interrelationships allows designers to explore trade-offs and synergies between different environmental impact categories, ensuring that improvements in one aspect of environmental performance do not inadvertently worsen others. By systematically analyzing and managing these interrelationships, designers can optimize ship designs to minimize overall environmental impacts while meeting performance requirements and operational objectives. This integrated approach enhances the effectiveness and sustainability of early stage ship design processes, supporting the development of environmentally responsible and economically viable vessels for diverse maritime applications.

2.4. Conclusion

In this chapter, an overview was provided of the different phases of a ship's lifecycle and the relevant aspects for conducting a comprehensive lifecycle assessment. Additionally, *Blended Design*, an early-stage ship design tool developed by *Ulstein Design and Solutions BV*, was introduced. While *Blended Design* offers valuable insights for ship design, it currently lacks a full lifecycle sustainability assessment component. To address this gap, an approach to integrate lifecycle sustainability assessment into the tool is being explored. To guide the search for the most suitable approach, criteria have been established to evaluate potential methods. In the following chapter, various lifecycle assessment methods will be discussed and assessed for compatibility with these criteria, aiming to identify the most promising options for enhancing ship design within the *Blended* framework.

3

Theoretical background of ship lifecycle perspectives, frameworks and their relevance

This chapter delves into the existing methods and frameworks for evaluating lifecycle environmental impacts in ship design. The aim is to assess these methods to determine their relevance for adding to *Blended*. Ultimately, this leads to a trade off between the different methods according to the criteria established in chapter 2.

3.1. Sustainability assessment methods and concepts

Different approaches are provided by the IMO targeting the improvement of environmental performance of maritime transport. Examples are the the Energy Efficiency Design Index (EEDI) or the Ship Energy Efficiency Management Plan (SEEMP) [13]. Nevertheless, a more complete assessment of the proposed improvement options should be based on a life cycle perspective. This would avoid burden shifting of environmental and economic impacts between different phases of the life cycle of maritime means of transport [14], as lowering one impact may result in a resulting increase in another. In this section, an overview of certain methods for sustainability assessment will be introduced and their relevance to ship design will be discussed.

Several theoretical frameworks and applications of sustainability assessments are known, focusing on a wide array of different industrial areas and life cycle phases of products. More than 30 different methods have been explored in various papers and by various authors, as was shown in a review paper by Zijp et al. (2017)[58]. On a product level, different studies identify different frameworks for executing a cradle-to-grave sustainability assessment. These include, among others, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Environmental Product Declaration (EPD) and Carbon Footprint of Products (CFP) [59]. Other identified frameworks in literature include Global Reporting Initiative and Corporate Social Responsibility [35]. Other terms heard are EcoDesign, Green Design, Environmental Design and Design for Environment (DfE) [60]. From these methods, all methods capable of addressing the environmental impact of products are chosen to further describe and investigate, focusing on applicability in *Blended* and relevance for ship design.

For the execution of sustainability assessments, the setting of requirements is an important part. This process, sometimes referred to as 'question articulation'[58] is preferably performed in cooperation with stakeholders included. In most circumstances. different complicating factors can be identified.

Different sustainability assessment methods are available which can fulfill the requirements set during the question articulation [58]. A combination of methods tailored to address the specific application could be proposed. In the case of *UDSBV*, a method is desired that quantifies the CO2 equivalent emissions over the complete lifecycle of a vessel. As was addressed earlier, Peeten [32] studied the design implications of taking into account the Well-to-Wake CO2 equivalent emissions of different fuels during operation in *Blended Design*. In order to make the most sustainable and conscious design decisions, a more comprehensive sustainability assessment is preferred, expanding the current design method with every phase of the vessel lifecycle, which were described earlier. After discussing different existing frameworks, the question articulation will be taken into account during the trade off of the different methods.

3.1.1. Life Cycle Thinking based methods

Multiple methods are based on Life Cycle Thinking (LCT). In this section an overview is given of LCT based methods which can be used in product design for the maritime domain.

LCA

Life Cycle Assessment (LCA) is the most commonly used method for sustainable design[14]. The principles and framework are defined in ISO 14040 [11]. A wide range of methods for implementation exist based on the framework defined in the ISO standard. LCA is aimed at assessing a product's environmental life cycle impact and providing quantitative data on a wide range of impact categories. The detail level of LCA is depending on the goal and scope definition. LCA provides a relative impact, owing to the functional unit element in the method. By having a relative approach, LCA differs from environmental performance evaluation or environmental impact assessment [11]. LCA is often combined with the economical assessment Life Cycle Costing (LCC) resulting in a integrated LCA-LCC approach [14].

Four phases are defined within the LCA analysis: Goal and Scope Definition (1), Lifecycle Inventory Analysis (LCI) (2), Impact Assessment (LCIA) (3) and Interpretation (4). These are shown in figure 3.1. The LCI consist of three stages: Goal and Scope Definition(1), Lifecycle Inventory Analysis (LCI) (2), and Interpretation (3). The CIA allocates Life Cycle Inventory (LCI) outcomes to various impact categories. For each category, a specific life cycle impact indicator is chosen and its result is computed. The compilation of these indicator results, known as LCIA results or the LCIA profile, offers insights into the environmental concerns linked to the inputs and outputs of the product system. Different methods to perform LCA have been developed for a wide range of proposes and applications. Some simplified methods allow for the assessment to be performed with less data and resources, resulting in more uncertain outcomes [60].

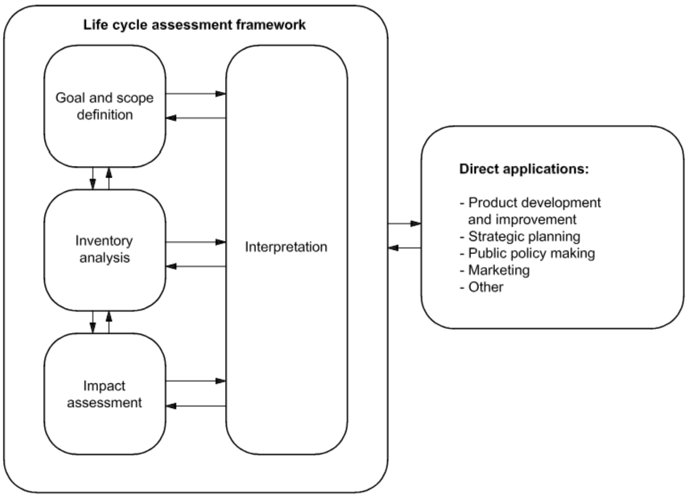


Figure 3.1: Stages of an LCA, retrieved from ISO14040 [11]

In the maritime context, different authors see implementation possibilities for LCA or the LCA-LCC integrated approach [14][35]. This method would allow for an optimization of environmental performance of the vessel, with a clear view on the economic effects of trade-offs made. The ISO standardized LCA is a widely recognized framework, which is used as a basis for different other methods [35] [61]. Also within the maritime context, standardized LCA assessments have been performed [44]. Besides, research has been done showing how LCA can be used complimentary to EEDI and EEOI as a tool to highlight vessel efficiency [13].

Assessing the ISO 14040 Life Cycle Assessment (LCA) method against the identified criteria reveals its strengths and areas for consideration. ISO 14040 offers a structured framework that accommodates various levels of data availability, addressing the criterion of ability to handle scarcity of data[11]. As a widely recognized and extensively used standard, ISO 14040 demonstrates maturity in its development and application[14]. Using an approach consistent with its guidelines and standardized procedures, ISO 14040 delivers reliable results. While ISO 14040 primarily focuses on a single scenario, it provides guidance on conducting sensitivity analyses and considering alternative scenarios[11], partially fulfilling the approach to alternative scenarios criterion. However, ISO 14040 may have limitations in addressing regional variability, as it emphasizes a global perspective and may not capture localized environmental impacts adequately. Given the method works with different performance indicators *Blended* also uses [11], ISO 14040 may integrate well with the *Blended Design* framework. Finally, ISO 14040 promotes a holistic approach to environmental assessment [14], considering interrelationships between lifecycle stages and environmental impacts.

Material Circularity Indicator

Material Circularity Indicator (MCI)[62] is an indicator developed to assess the circularity of a product and materials, MCI also allows for a more comprehensive assessment of a product, including the environmental risks of a design. Because of this, MCI can also be used as a sustainability assessment tool. The Material Circularity Indicator (MCI) differs from LCA methods in several respects while also sharing some similarities. While LCA assesses the environmental impacts of a product across its life cycle under various scenarios, MCI mostly focuses on the flow of materials throughout the use of a product [62], as circular thinking goes beyond the lifecycle of a single product. It emphasizes the utilization of recycled or reused materials and promotes recycling or reusing at the product's end of life, taking into account factors such as durability and usage intensity. Moreover, the MCI emphasizes the preservation of biological systems as sources of continually replenished material flows[62].

Many of the input data required for LCA overlap with those for the MCI and complementary impact indicators may be derived from a LCA approach (such as standards to assess a product's carbon footprint). The other way around the MCI could potentially serve as one of the output parameters in a LCA or eco-design framework alongside existing metrics[28]. These complementary indicators are typically chosen at the product level, but they can also be applied at the company level if appropriately aggregated for a product range.

In research done by Hoffmann (2023)[63], an adjusted version of MCI was developed, aiming at incorporating circularity in ship design processes. The thinking behind the method is relevant, as including the impacts of the product beyond its initial lifecycle within an environmental assessment increases the validity of the assessment. However, to quantify the environmental impact as targeted in this research, the MCI method involves using LCA or EPD [28].

Specific scarcity handling mechanisms are not explicitly defined. MCI is relatively new, further refinement and validation are needed to enhance its maturity. For incorporating a full life cycle consideration, adjustments like those proposed by Hoffman (2023) [63] have to be implemented. Its reliance on widely established LCA methods contributes to reliability of the results. However, like any evolving method, continuous validation and improvement are essential. The MCI considers circularity within LCA, allowing for scenario analysis. It can assess different product designs, material choices, and end-of-life options. However, explicit guidance on handling alternative scenarios could enhance its applicability. The MCI's applicability is not inherently region-specific. It can be adapted to various contexts, including regional differences in material availability, recycling infrastructure, and consumer behavior. The MCI considers circularity-environmental interrelationships, by combining LCA and circularity metrics, it assesses both aspects simultaneously. As circularity lies beyond the scope of this research, including MCA in *Blended* is not directly relevant, but it is promising for the future development and expansion of the tool.

Basurko proposition

Basurko et al. (2014) [35] proposed a framework tailored for marine technologies to perform a life cycle sustainability assessment. Efforts were made to address issues of absence of clear experiences and guidelines, as well as conflicting criteria for sustainable marine technologies [35]. This resulted in the introduction of a quantitative and holistic approach to sustainability assessment.

The proposition consists of 8 steps: Scope (1), Identification of vectors (2), Data collection (3), Assessment (4), Modeling (5), Indices (6), Weighting (7) and Decision Making (8) [35]. Three sustainability dimensions are identified: Environment (1), Economy (2) and Social(3). The initial five steps are individually implemented across all sustainability dimensions and targeted systems or technologies. In Step 6, as result of the previous steps, three distinct sustainability indices will be found, each reflecting the performance of the related specific sustainability dimension. These indices are weighted in step 7 before taken into account during decision making.

The initial phase involves defining the study objectives and the relevant technologies, detailing system descriptions, technology characteristics, and study parameters. Following this, the system is analyzed for all potential vectors (variables and parameters) that could contribute to the environmental impact and could have cost implications. In step 3, data is assigned to these vectors. The evaluation in step 4 is done by performing a LCA. As data collection and assessment are both time consuming activities, a modeling step is foreseen where mathematical models of the environmental impacts can be made. These models can be used as estimation of the impact in different scenarios, without the need of doing additional assessments. Assessment results allow for comparison of sustainability performance within specific dimensions, but require normalization to regulatory standards to obtain numerical outcomes. Therefore, step 6 leads to the generation of three sustainability indices: Environmental, Economic, and Social Sustainability Indices. The three indices from Step 6 can be weighted to align with political, legislative, or user priorities, resulting in a holistic Index of Sustainability. While ISO 14044 offers optional weighting in LCA studies, it’s intrinsic to Step 4 of the proposition; subsequently, multi-criteria decision-making follows, allowing for adjustments and comparisons to select the most sustainable alternative.

A graphical representation of the proposition can be found in figure 3.2, illustrating how the various methodological steps for different indices are executed and how they influence decision-making. The assessment used in this proposition is LCA, as the author considers it to be the most suitable, being the most commonly accepted method used for assessing the environmental sustainability of a product or process [35]. Cost-benefit analysis has been added to evaluate costs within the proposed method. However, as LCA was chosen to be primarily used as sustainability assessment, it is suggested that using LCC would be more appropriate [35].

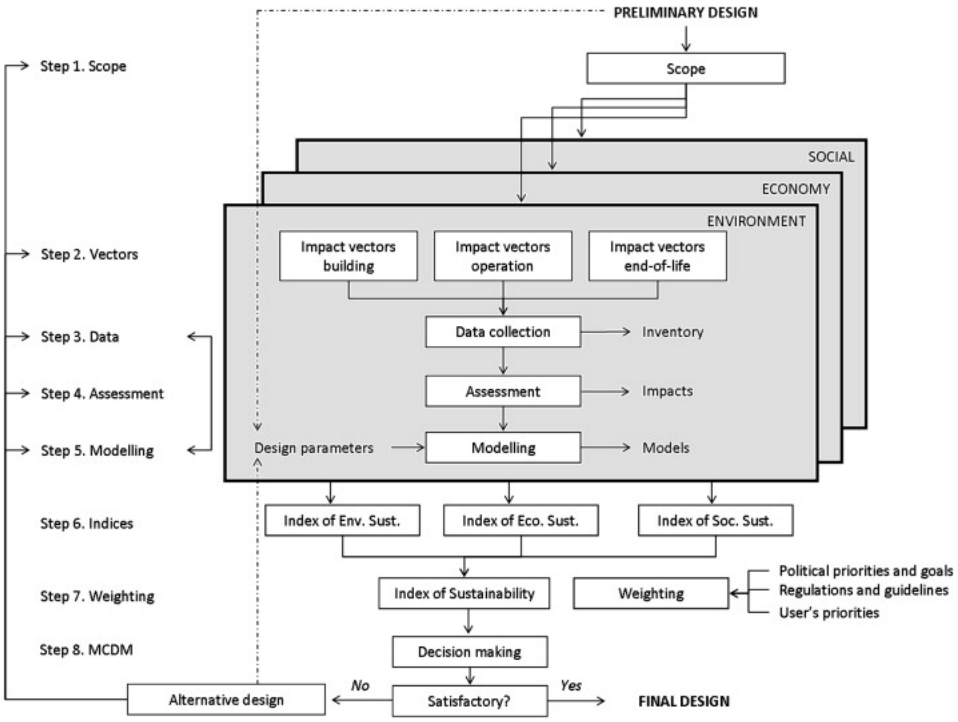


Figure 3.2: Life cycle assessment as proposed by Basurko et al. (2014)[35]

As the proposition was made to be used in a maritime context, it can be regarded as relevant. The approach incorporates quantitative methods such as life cycle assessment (LCA) and economic evaluation. While these methods require data, the method's flexibility allows for adaptation when data is scarce. It emphasizes robustness even with limited information. Basurko's proposition integrates established LCA techniques and economic evaluation. Although it may not be as mature as widely used methods, its holistic approach and implementation of matured and accepted methods contributes to its development. By combining environmental, economic, and social aspects, Basurko's proposition aims for comprehensive results. However, its reliability depends on data quality and assumptions made during the assessment and the modeling step. Basurko's proposition allows for scenario analysis by considering different sustainability dimensions. Users can explore alternative scenarios by adjusting input parameters. While Basurko's proposition does not explicitly address regional variations, its adaptability enables users to incorporate regional data if available. Basurko's approach is flexible and its compatibility with *Blended* is similar as for other LCA based methods.

Carbon Footprint Assessment

The International Organization for Standardization (ISO) developed the ISO14060 family for quantifying and reporting and verifying of GHG-emissions, called the Carbon Footprint of a Product (CFP). ISO14067 aims to quantify the GHG-emissions related to all life cycles of a product [64]. The principles, guidelines and requirements of the ISO standardized LCA method form the basis of CFP. In a way, CFP is a specified LCA method with GHG-emissions as only impact category. Other environmental impacts as result of the lifecycle, as well as social or economic impacts are not assessed. In figure 3.3 the relationship between different ISO14000 families is shown, where CFP related communication is addresses by ISO14026 and development of product categories by ISO14027[65].

ISO14067 defines CFP as follows: *'sum of GHG emissions and GHG removals in a product system, expressed as CO2 equivalents and based on a life cycle assessment using the single impact category of climate change'*[65]. The general method to conduct a CFP study includes the same four phases as in LCA. ISO14067 was identified as one of the most important GHG-emissions related life cycle tools by [66] for application on ships. No specific studies were found supporting the stand alone implementation of CFP in shipbuilding.

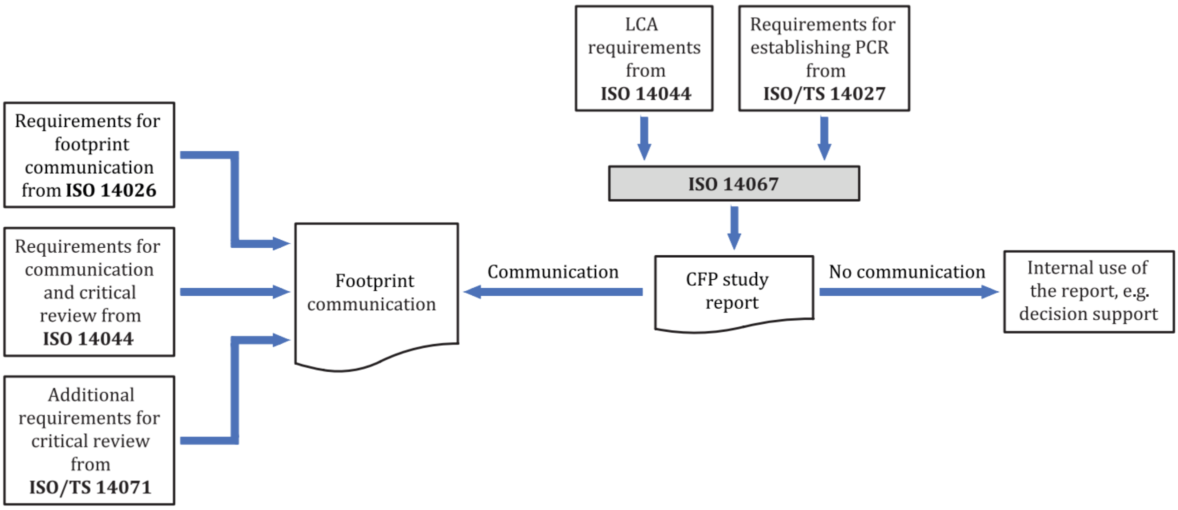


Figure 3.3: Relationship between ISO14067 and standards beyond the GHG management family of standards, retrieved from ISO14067 [65]

ISO 14060 emphasizes a life cycle perspective, which allows for adaptation when data is scarce. It provides guidelines for quantification and reporting of the CFP, considering environmental impacts throughout a product's life cycle. ISO 14060 is part of the ISO 14000 family, which includes established

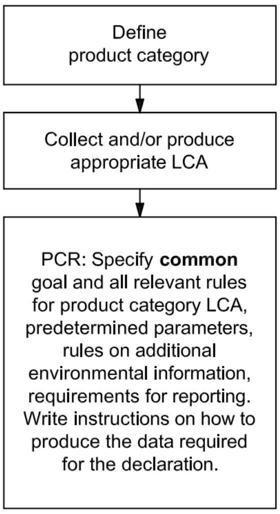


Figure 3.4: Steps in preparation of a PCR document, retrieved from ISO14025 [67]

standards for environmental management. While ISO 14060 itself is relatively new, its alignment with ISO 14040 and ISO 14044 LCA standards contributes to its maturity. By following ISO 14040 and ISO 14044, ISO 14060 aims for robust and consistent results. However, reliability depends on data quality and assumptions made during the assessment. ISO 14060 does not explicitly address regional variations. However, its flexibility enables users to incorporate regional data if available. ISO 14060 considers the interplay between life cycle stages, emphasizing completeness, consistency, and transparency. It aims to avoid double-counting and ensures a holistic view of carbon emissions. As LCA requirements of ISO14040 are used in setting up CFP reports [65], the added value of using ISO14060 is largely standards in reporting and communication.

Environmental Product Declaration

An Environmental Product Declaration (EPD) or type III environmental declaration is another standardized quantification method for environmental impact assessment [62]. EPD operates as a standardized tool to communicate the environmental impact of a product throughout its life cycle. It typically includes data on resource use, energy consumption, emissions, and other relevant environmental metrics. EPD can be seen in the first place as a reporting format, where LCA is performed as sustainability assessment[61]. EPDs are internationally standardized as an ISO 14025 type III environmental declaration. ISO14025 defines a type III environmental declaration as 'providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information' [67]. The most significant addition of performing an EPD compared to an LCA is the establishment of product category rules (PCR). These PCR are either developed before performing the assessment or, whenever an product specific PCR exists, the existing PCR is applied. After defining the product category, an LCA is performed which is used as basis to make a PCR by specifying a common goal and rules for the product category LCA. These product category rules are fixed and ensure better comparability among future assessments [67].

For shipbuilding, EPDs could be highly relevant as a reporting format that allows stakeholders to assess the environmental footprint of ships, considering factors such as raw material extraction, manufacturing processes, transportation, use phase, and end-of-life disposal or recycling. By providing transparent and comparable information, EPDs enable decision-makers to make informed choices that prioritize environmental sustainability in shipbuilding practices. However, as an EPD officially has to be obtained after verification of EPD International, there is no relevance of obtaining an EPD after a LCA study in an early stage design phase where a big number of designs has to be analyzed. The underlying type iii environmental declaration method does however provide a useful framework for maritime applications. Where the complexity of ships often leads to issues related to the functional unit and performance indicators when performing LCA studies, having a clear PCR and validated PCR enables subsequent LCA studies to be performed more easily[68].

The EPD method allows for adaptation when data is scarce, emphasizing robustness and ensuring comparability by setting standards. While the EPD itself may not be as mature as widely used methods, its alignment with LCA standards contributes to its development. Like for other methods, reliability primarily depends on data quality and assumptions made during the assessment. The EPD allows for scenario analysis by defining the product using appropriate PCRs. Users can explore alternative scenarios by adjusting input parameters. Although the EPD doesn't explicitly address regional variations, its flexibility would enable users to incorporate regional data if available. As EPD aligns with LCA, compatibility with *Blended* is comparable. The EPD considers the interplay between life cycle stages, ensuring a holistic view of environmental impacts. It provides a structured framework for managing these interrelationships.

Product Environmental Footprint

The Product Environmental Footprint (PEF) and Environmental Footprint (EF) are the methods recommended by the European Commission (EC) as a common way to quantify the environmental impact of goods and organizations based on LCA [69]. The objective of these methods is to establish a standardized approach for evaluating environmental impact, with potential future integration into anticipated EU policies. In the phases PEF, the drawn from LCA is clearly visible. These phases, shown in figure 3.5 are inline with the ISO LCA guidelines. PEF however goes a step further by providing a detailed method for performing the LCA and adding product specific requirements for better comparability between products, inline with the objective of Product Environmental Footprint Category Rules (PEFCR) to do environmental assessment with a consistent and specific set of rules.

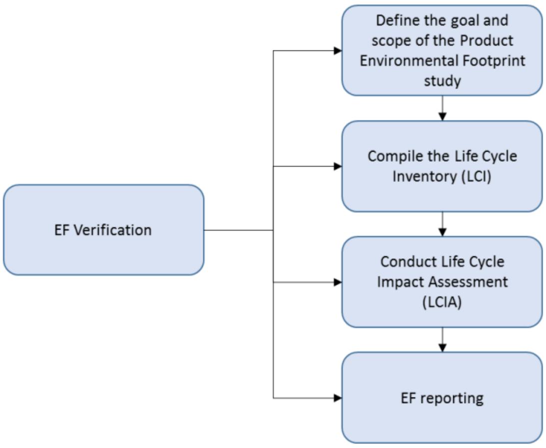


Figure 3.5: Phases of a product environmental footprint (PEF) [70]

The method specific normalization factors are seen as the biggest challenge of PEF. These normalization factors qualifies the relevance of an impact compared to the global impact of the product, meaning that a low impact relative to global scale will be seen as less critical as a high impact relative to global scale[71]. This could lead to the negligence of certain environmental impacts that are not negligibly small. Besides, other issues standing in the way of widespread adaptation are inadequate product category rules within the method, biodiversity and indirect land use impacts missing in the assessment, preventing a full comprehensive assessment when desired. For the current research these impacts our out of scope. Other practical issues are the effects on the LCA study costs and unclarity about communication of the results[71].

As a LCA method with added product specific requirements and calculation rules the method can be relevant for performing on complex systems like vessels. By applying the PEF method, ship designers can make more informed decisions to improve the environmental sustainability of their designs. However, the limitations of the method would suggest opting for a more matured method. No studies or cases are know where PEF was applied in a maritime context.

Both PEF and EF are Life Cycle Assessment (LCA) based methods, and handle scarcity of data similarly. Although PEF and EF are relatively new, they align with established LCA standards, Their development benefits from existing LCA knowledge. PEF and EF aim for robust results by considering multiple environmental dimensions. However, reliability depends on data quality, assumptions, and adherence to methodological guidelines. Both methods allow scenario analysis. PEF focuses on products (goods or services), while EF extends to organizations. Users can explore alternative scenarios by adjusting input parameters. While PEF and EF don't explicitly address regional variations, their adaptability enables users to incorporate regional data if available. PEF and EF consider the interplay between life cycle stages, emissions, and waste streams. They provide a structured framework for holistic environmental assessment.

Ecodesign

A research group at TU Wien developed their own method for Ecodesign, in the first place directed at design of consumer products. Ecodesign is referred to as a process that aims to design while using available resources intelligently for maximum benefits with minimal environmental impact [72]. The basis for the design method is the ErP-Directive[73], which addresses the energy efficiency and product-specific standards of energy using products. Within Ecodesign, five stages of the product lifecycle are examined: use of raw materials(1), manufacture(2), distribution(3), use(4) and end of use(5). Every stage is analyzed using existing standards like LCA and CFP.

The analysis results in an environmental profile where the impact of the different stages on the total lifecycle are shown, identifying the highest impact life cycle stages helps finding the life cycle parts where action would lead to the highest possible impact reduction. Ecodesign specifically addresses the design stage of the product, aiming for a more conscious designed product and is not intended to be used on existing products. Besides, Ecodesign additionally focuses on stakeholders involved.

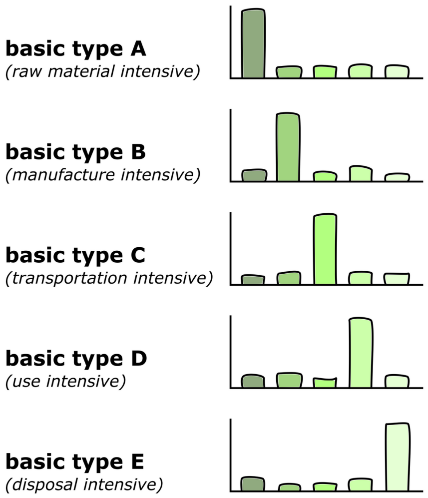


Figure 3.6: The Ecodesign analysis results in identifying the lifecycle stage with the highest impact, enabling targeted interventions. Retrieved from [72].

No records of the implementation of Ecodesign on ships was found. As LCA based method it provides a holistic perspective on the lifecycle of the system. The broader scope of Ecodesign compared to a simple LCA would allow for a more comprehensively assessed design, especially when different stakeholders need to be taken into account. The use of different methods for different types of assessments within Ecodesign increases complexity.

The Ecodesign approach at TU Wien integrates quantitative methods, aiming for robustness even with limited data. It considers environmental impacts across product life cycles. While Ecodesign is relatively new, its alignment with established LCA standards contributes to its development. Ecodesign aims for robust results by combining environmental, economic, and social aspects. However, reliability depends on data quality and assumptions. Ecodesign allows scenario analysis, considering both product improvements and new developments. It follows a structured process with five steps. Although

Ecodesign doesn't explicitly address regional variations, its adaptability enables users to incorporate regional data if available. Ecodesign is compatible with *Blended* methods similar as for other LCA based methods. Its focus on minimizing environmental impact contributes to broader sustainability assessments. Ecodesign considers the interplay between life cycle stages, but is not fully tailored for considering interrelationships.

Ecological footprint standards

The Ecological Footprint Standards 2009 form a a set of internationally recognized ecological footprint (EF) standards. The 2009 Ecological Footprint Standards are made to guarantee the consistent production of Footprint assessments in alignment with best practices proposed within the applicable fields [74]. By implementing EF standards, it is tried to reach maximal accuracy and transparency in conducting and conveying assessments by making standards and guidelines related to aspects like sourcing data, deriving conversion factors, setting study boundaries, and articulating findings. These standards apply universally to all Footprint studies, including sub-national populations, products, and organizations.

The Ecological Footprint of a final product is defined as the cumulative footprint of all activities necessary for its creation, use, and disposal[74]. This assessment can also be conducted for intermediate products, encompassing activities up to a certain point in their value chain. Due to the complexity and duration of product cycles, any assessment provides a simplified view and requires a defined life cycle and associated activities. Two main approaches for calculating the Ecological Footprint are process-based life-cycle assessment (P-LCA) and environmentally extended input-output life-cycle assessment (EEIO-LCA)[74]. P-LCA offers detailed analysis but may lack complete upstream coverage, while EEIO-LCA provides full upstream coverage but may lack product specificity. Both approaches, as well as hybrid methods, are compliant with ISO 14040 and 14044 standards, thus meaning that the environmental impact assessment of EF equals LCA.

As the method is practically the same as LCA, the applicability and relevance for ship design is the same as for LCA. The approach emphasizes robustness even when data is scarce. The method considers environmental impacts across product life cycles and allows adaptation. The standards align with established LCA standards. Reliability largely depends on data quality and assumptions made during the assessment. The standards allow scenario analysis, considering both products and organizations. Users can explore alternative scenarios by adjusting input parameters. While the standards don't explicitly address regional variations, their adaptability enables users to incorporate regional data if available. As the Ecological Footprint Standards align with LCA principles, making them compatible with *Blended* similarly.

3.1.2. Alternative Environmental Evaluation Methods

Emergy

Assessment based on emergy is a concept developed in the 90s for environmental decision making. Emergy is the availability of energy that is directly and indirectly used to make a product of service [75]. Emergy is expressed in emjoule, a unit to express this available energy used in transformation processes to make a product. All types of energy used in processes, coming from fuel, electricity, human activity are, for example, all expressed as emjoules of solar energy that was required to produce each. Other common bases for energy can also be used, such as coal emjoules or electrical emjoules, although this is not often done [75]. By focusing on the energy used as an environmental indicator, the method contrasts with common lifecycle indicators where focus lies on the environmental impact as result of the resources. The main focus of the assessments are on the donor side, considering the efforts made by nature to support a design. This shifting of focus to the upfront impact of the resources would allow for a clear assessment and comparison, without the need to find weighting factors or determining material intensity factors. The analysis would also include the emergy required to handle pollutants coming from the product. Ultimately, during decision making the total emergy is considered. Indices could be added to couple emergy to environmental or economical parameters.

No literature was found providing evidence for emergy analysis was ever performed in the maritime context. As ecodesign method, it could be useful in shipdesign. However, the focus on the upfront impact would not fully align with energy using products, especially not vessels where the impact of the operational stages are largest. Depending on the system boundaries identified, emergy assessment is useful to assess the impact on the geosphere.

Emergy Analysis tends to be robust in handling data scarcity. It relies on a holistic approach that considers both natural and human contributions. Even when specific data points are missing, emergy accounts for the overall ecosystem services and energy flows, providing a comprehensive view. Emergy Analysis has been developed over several decades and has matured significantly[75]. Researchers have refined its concepts, applications, and calculations. However, it remains a specialized method, and widespread adoption varies across disciplines. Emergy Analysis provides reliable results when applied correctly. Its strength lies in capturing ecological contributions and emphasizing the role of natural systems by analyzing upstream flows [76]. However, like any method, it requires skilled practitioners to ensure accurate assessments. Emergy Analysis allows for exploring alternative scenarios. By adjusting input parameters (such as energy sources, ecosystem boundaries, or system boundaries), analysts can assess different pathways and evaluate trade-offs. Emergy Analysis acknowledges regional variability explicitly [75]. It considers local ecosystems, resource availability, and environmental conditions. However, the quality of results depends on the availability and accuracy of regional data. Emergy Analysis inherently considers interrelationships. It accounts for the interconnectedness of natural processes, energy flows, and human activities. By doing so, it provides insights into the broader context of environmental impacts [75]. However, the current lack of parameter expression regarding energy flows in the *Blended* tool significantly reduces compatibility, as substantial effort would be necessary to align it with *Blended* parameters. Besides, not focusing on the operational performance would not limit burden shifting of environmental impacts in energy using products like ships and further reduce compatibility with *Blended*.

Material Flow Analysis

Material Flow Analysis (MFA) is an industrial ecology based concept that studies material and energy flows of a system. Based in Material Intensity per Service Unit MIPS, MFA evaluates the environmental impact of processes related to raw materials used in a product. Each input of the system, being energy or material, are multiplied by a material intensity factor (g/unit)[76]. Respectively, this expresses the overall quantities of abiotic matter, water, air and biotic matter necessary to support the specific process under examination. MFA involves tracking physical units like material quantities, resulting from processes like extraction, production, transformation, consumption, recycling, and disposal within a given system. The analysis may target a singular substance (e.g., carbon dioxide), naturally or technically transformed materials or finished products.

However, MFA has limitations, as it fundamentally assumes that, over a given period, inter-sector flows from one sector to another are proportional to the total output of the receiving sector for that same period[76]. MFA could be a useful addition to a life cycle sustainability assessment, providing insights into resource optimization opportunities. In figure 3.7 an integration scheme of LCA, Emergy and MFA is shown. LCA focuses on downstream flows (the products produced), where MFA focuses in upstream flows (the resources needed for production). Emergy also focuses on upstream flows, but may include downstream flows [76].

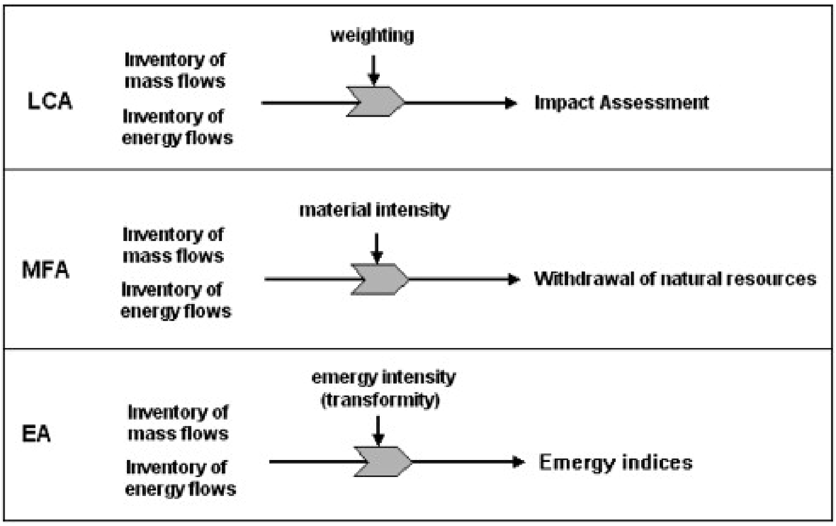


Figure 3.7: LCA, MFA and Emergy retrieved from Almeida et al. (2010)[76]

Assessing the MFA method against the identified criteria reveals its strengths and areas for consideration. As MFA considers material flows, the lack of a detailed understanding of materials present could lead to incomplete results. Developed over several decades, MFA has evolved into a mature method widely used and applicable across spatial and temporal scales, making it a core method in industrial ecology and urban metabolism. When correctly applied, MFA yields reliable results, complementing economic accounting by tracking stocks and flows of materials while considering both material and non-material aspects. Additionally, MFA considers different scenarios by implementing different . Furthermore, MFA considers regional variability, acknowledging the importance of accurate regional data for quality assessments. MFA inherently considers interdependencies within material flows, lacking the connection with other relevant processes and aspects.

Environmental and Socioeconomic Impact Assessment

Environmental Impact Assessment (EIA) is a framework for examination and assessment aimed at evaluating the potential impacts of project to promote sustainability[77]. Conducting an EIA, allows to anticipate and prevent environmental issues as a result of wrong decision making. The general process consist of three phases, Preliminary Screening(1), Environmental Assessment(2) and Environmental Impact Review(3).

A Socioeconomic Impact Assessment (SEIA) considers the benefits and negative impacts for a whole community. This systematic analysis can be used as extension to EIA. Socioeconomic cost is evaluated against socioeconomic benefit [77]. The focus of the method, as the name suggests, is on social and economic impacts of a products on society. Environmental consequences for these impacts are also taken into account. As such, the method covers all domains of sustainability. The important socioeconomic categories are health and well-being, sustainable wildlife harvesting, land access and use, protection of heritage and cultural resources, business and employment opportunities, sustainability of population, services and infrastructure, ample sustainable income and lifestyle [78]. The main feature of socioeconomic impact assessment lies in expressing all identified impacts in economic terms. Because of that, this approach differs from other methods in its fundamental scientific and technical nature. The six steps of SCIA are Scoping(1), Profiling Baseline Conditions(2), Predicting Impacts(3), Identifying mitigation(4), Evaluating Significance(5), Applying Mitigation & Monitoring(6).

No studies were found about the application of SEIA in a maritime context. Although the motivation of the method is clear, the method is not made to be used outside its intended scope: assessing the impacts op project and developments within the Mackenzie Valley, Canada and is aimed to be performed in close contact with the local authorities. Therefore the relevance for shipbuilding is low.

Assessing the EIA and SEIA methods against the identified criteria reveals their strengths and considerations. Both methods demonstrate the ability to handle scarcity of data by conducting holistic assessments and considering various environmental and socio-economic factors. EIA benefits from its long-standing presence and global acceptance, indicating a Mature method, whereas SEIA's maturity depends on regional adoption and specific project contexts. When conducted by skilled practitioners, both EIA and SEIA provide reliable results, ensuring robust assessments of environmental and socio-economic impacts. Both methods allow for the exploration of alternative scenarios, enabling analysts to assess different pathways and trade-offs. They also exhibit sensitivity to regional variability, considering specific ecosystem or socio-economic contexts. Additionally, both EIA and SEIA inherently address the management of interrelationships, recognizing the interconnectedness of environmental and socio-economic factors.

Material Intensity per Service Unit

Material Intensity per Service Unit (MIPS) serves as a method for assessing the environmental impacts linked to a product, process or service. MIPS aimed to promote the concept of dematerialization across various scales. In evaluating the environmental impact of manufacturing and service provision associated with a product, MIPS expresses the quantity of materials and resources utilized. By aggregating all materials involved, MIPS provides a holistic measure of a product or service's material intensity, expressed as the ratio of total material input to the number of service units[77].

No application in a maritime context is known. It could be a valuable tool for assessing the sustainability of ship design, offering insights into resource efficiency and environmental impacts across the vessel's life cycle. However, its applicability to this context faces certain challenges. While MIPS provides a comprehensive view of material consumption relative to service provision, the complexities of a vessel design, construction, and operation may not be fully captured by this method. As ships have long life spans, complex supply chains, and diverse operational requirements, it is difficult to precisely quantify material intensity per service unit. Additionally, MIPS primarily focuses on material efficiency and overlooks other critical sustainability aspects in ship design, such as energy efficiency, emissions reduction, and end-of-life considerations which are in the scope of this research. Despite these limitations, MIPS can still offer valuable insights into resource optimization opportunities and guide decision-making processes in ship design towards more sustainable practices when used in together with other life cycle sustainability assessment methods made to the maritime industry's specific needs.

MIPS has evolved into a mature method applicable across various scales in the last 30 years, thus meeting the criterion of mature method. When correctly applied, MIPS yields reliable results, capturing both material and non-material ecological impacts. MIPS provides a robust framework for assessing resource use in products and services, but its ability to handle alternative scenarios depends on context and assumptions. MIPS considers regional variability as well as interdependencies. MIPS compatibility with *Blended* is limited, as performance indicators used are different. Besides, the environmental impacts in the scope of this study are not directly addressed.

Strategic Environmental Assessment

Strategic Environmental Assessment (SEA) is a systematic approach to evaluating the environmental impacts of programs, plans or policies, integrating economic and social factors during decision-making[77]. It offers alternatives to address environmental challenges, supporting low-carbon sustainable development. SEA surpasses traditional Environmental Impact Assessments by managing interactions and cumulative impacts more effectively. The SEA framework comprises screening, scoping, and analysis phases. Scoping defines assessment boundaries and stakeholder engagement, while analysis involves baseline documentation, impact evaluation, and institutional capacity assessment. Challenges include data scarcity, public involvement, and uncertainty. Despite these, SEA enhances decision-making by providing informed recommendations and ongoing monitoring post-implementation [77].

Assessing Strategic Environmental Assessment (SEA) against the identified criteria reveals its strengths and areas for consideration. SEA demonstrates a robust ability to handle scarcity of data by systematically integrating environmental considerations into policies, plans, and programs, thereby addressing data scarcity through a holistic approach that considers overall resource consumption and inter-linkages with economic and social aspects. Developed over several decades, SEA has evolved into a mature method widely used globally and considered a core method in achieving sustainable development, thus meeting the criterion of mature method. When correctly applied, SEA yields reliable results by integrating environmental concerns into appropriate plans and programs, contributing to wider aims of environmental protection and UN Sustainable Development Goals. Additionally, SEA excels in its approach to alternative scenarios, allowing exploration of alternatives such as balancing resource use and considering socio-economic impacts, thus helping decision-makers understand trade-offs. Furthermore, SEA explicitly considers regional variability, adapting to specific contexts and local ecosystems, while also inherently considering interdependencies and evaluating the broader environmental context. However, as SEA is primarily used in the context of policy development. It mainly helps assess the environmental implications of proposed policies, plans, and programs before they are implemented. Because of this, the applicability of the framework for ship design is limited. No literature was found to support the applicability of SEA for product design.

Multi Criteria Analysis

Multi criteria analysis (MCA) is an approach used to analyze overall possible alternatives and preferences and evaluate them under different criteria simultaneously[77]. In this method, preferable targets and goals are particularized and corresponding characteristics and indicators are recognized [79]. An important aspect of MCA is its reliance on quantitatively analyzing different impact categories to assess indicators. However, in most instances, these indicators are not expressed in economic terms[77]. Within MCA, diverse methods are employed to categorize, compare, and determine the most suitable alternatives based on given criteria. Depending on the chosen approach, each criterion can undergo qualitative or quantitative evaluation [80]. MCA serves as a tool, proving particularly effective in areas and sectors where single-criterion methods are ineffective. It is especially valuable in instances where crucial social and environmental impacts resist quantification in monetary terms [77].

As MCA aids in decision making processes, it is not inherently a life cycle sustainability assessment approach. It can be implemented in new propositions, also in the context of early-stage ship design tools. MCA may not be directly applicable when seeking a new approach for Life Cycle Sustainability Assessment. However, its underlying principles and method can serve as valuable inspiration when developing innovative approaches.

3.1.3. Cost based methods

As extension beyond comprehensive environmental assessment, cost based life cycle methods are developed. Different cost assessment methods for products exist, including Cost-Benefit Analysis, Comparative Value analysis and Net Present Value.

Life Cycle Costing

A method used to assess the total cost of ownership of a product or asset over its entire life cycle, from acquisition to disposal, is Life Cycle Costing (LCC). Cost-benefit analysis has also been employed to evaluate costs within this framework, aiming to optimize the trade-offs between the environment and the economy. However, LCA has been widely embraced in sustainability assessments, as it aids in mitigating long-term environmental costs. LCC may therefore be more fitting as a method within the life cycle context, while LCA serves a broader purpose, including assessing the sustainability of a product [35]. Unlike traditional costing methods that only consider upfront purchase costs, LCC takes into account all costs incurred throughout the life of the product, including maintenance, operating, repair, and disposal costs. By considering both present and future expenses, LCC enables decision-makers to make informed choices that optimize long-term value and minimize overall costs. This approach is particularly valuable in industries with significant operational and maintenance expenses, including shipbuilding.

LCC is a widely used tool for cost based life cycle assessments [14][35]. Experience of applying the method in a marine context can already be found in research by Utne et al. (2009)[81]. No standardized approach exists except ISO 15686, which is made to standardize LCC within the construction sector. LCC largely follows the methodological steps of LCA, but lacks a component Impact Assessment [82]. The approach used by Utne [81] for assessing the costs of a fishing vessel can be seen in figure 3.8.

Various studies indicate the potential for integrating life cycle costing (LCC) and life cycle assessment (LCA), even within the maritime sector [14]. This combination offers a comprehensive approach to evaluating both the economic and environmental aspects of maritime operations. By considering life cycle costs alongside environmental impacts, decision-makers can make more informed choices regarding

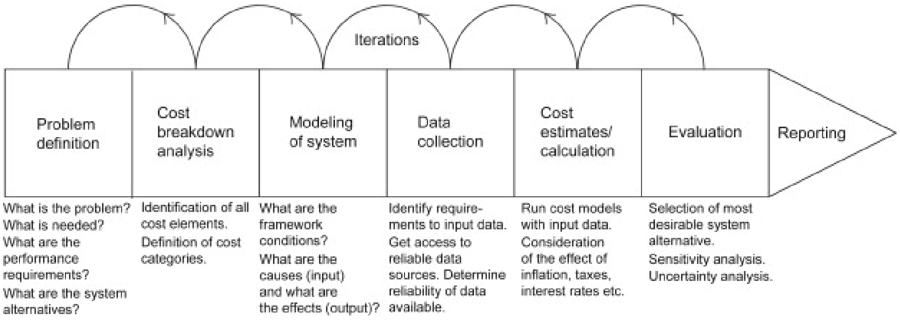


Figure 3.8: LCC approach as followed for a fishing vessel by Utne et al. (2009)[81].

sustainability and efficiency in maritime activities. For both LCA and LCC procedures, application of the assessments in ship design is demanding, at the same time one analysis taking into account environmental, economic and energetic aspects would be preferred. Therefore, Gualeni et al. (2018)[83] introduced Life Cycle Performance Assessment (LCPA). LCA and LCC analyses are separately performed, and environmental, energetic and economic KPIs are evaluated before being merged in a final global LCPA Index.

A combination of LCA and LCC by introducing eco-costs, assigning economic values to environmental impacts in LCA [84]. By doing this, effectively a single score LCA is created, expressing all life cycle aspects in monetary value. Also other propositions for an 'environmental LCC' have been brought forward [82]. An initial challenge is a result of different units of measurement utilized in the analysis. While LCC gives results in currency, environmental impacts vary depending on the type of pollutant assessed, complicating comparisons between different solutions, particularly in ship design. Additionally, there is a risk for double-counting when environmental impacts are expressed into both financially and physically [83]. Besides, influenced by currency values across countries and over time, the cost data has a certain volatility which leads to additional complexities.

In industries beyond the maritime sector, the utilization of LCA and LCC is typically more developed. In the car and automotive industry developed this leads to the establishment of Full Cost Analysis (FCA)[85]. In this method, the internalization and externalization of various impacts of products and services occur, leading to adjustments in prices accordingly. A decisions has to be made which impacts are taken into account when performing FCA. The biggest difficulty during FCA lies in assigning monetary values to environmental and social concerns. As a result, its practical applicability appears limited to particular scenarios, such as those involving well-documented shipyards and ship types, facilitating straightforward data collection[83].

Gualeni et al. (2018)[83] proposes to create a ship breakdown structure (SBS) with different detail levels, corresponding with detail levels during the concept design of ships. LCC and LCA are combined by expressing environmental and economic KPIs for the same functional unit. Moreover, Key Performance Indicators (KPIs) are weighted and restricted to ensure compliance with regulatory requirements, while also allowing for the customization of importance levels based on the preferences of the designer or client. A linear combination of economic and environmental sub-indexes previously evaluated through KPIs calculation leads to a Life Cycle Performance Assessment Index.

Other cost based methods

Other cost based methods, like Cost Benefit Analysis (CBA) focus on the expenses and advantages of a project from a purely economical way. All costs and benefits of a product over its lifecycle are expressed in monetary units, where benefits are all revenues obtained from a project. These methods mostly focus on finding the highest return on investment. Within CBA, the following steps can be described: analyzing cost and benefits, assignment of monetary values to cost, assignment of monetary values to benefits, and, finally, comparison of cost and benefits [77]. An schematic overview of the steps in a CBA can be found in figure 3.9.

Cost based life cycle assessment is an important and integral part of ship design. In *UDSBV*'s design tool a cost assessment is also performed. As complementary method to LCA, LCC fits in the same

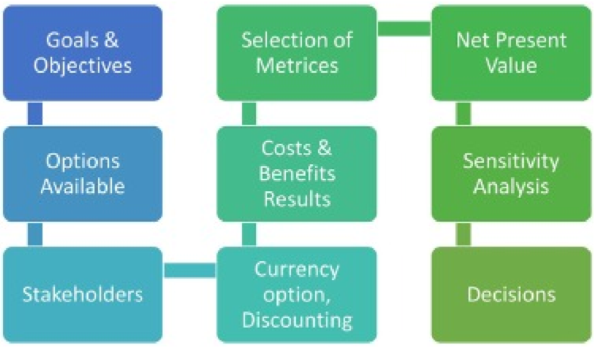


Figure 3.9: Steps in a CBA, retrieved from Nautiyal et al. (2021)[77].

framework, leading to the assumption LCC may be more appropriate. The results of an LCC can be used in and Net Present Value (NPV) or Return on Investment (ROI) calculation.

3.2. Applications of Life Cycle Sustainability Assessments

Within the maritime context, Fet et al. (1997) [86] performed the first LCA which concerned shipping vessels. As earlier performed studies mainly focus on the quantification of impacts during either the vessel manufacturing process or the operational phase, the number of comprehensive LCA studies performed remains limited. A complete lifecycle assessment remains complex and there is a lack of specialized tools which can be used within the maritime industry [87]. Uncertainties about end of life, and development of emerging end of life technologies complicate material flow analyses. Operating in different geographical areas influences the environmental performance [48], leading to additional challenges for an already complex system. The system itself already has a high level of complexity which can result in the reduction of reliability of the assessment. A wide range of interdependent subsystems, different modes of operation, gradual performance reduction due to fouling, maintenance and conversions all affect the solidity of the assessment. Issues related to functional unit or boundary determination are strongly amplified by the complexities faced when performing a life cycle sustainability assessment within a maritime context [88].

The derivation of results which are reliable is important for different reasons. When applying lifecycle assessments in early stage ship design, aiming for concept comparisons, it is essential that correct information is provided to include in the decision process. Moreover, if any regulations were to become active or expanded with life cycle impact restrictions in the future, regulatory compliance could only be assessed when reliable results form the basis of the comparison.

The choice of system boundaries, functional unit and scope is left to the person performing the assessment[48]. A wide range of assessments have been performed, mainly Life Cycle Assessment based on ISO 14040 [14][88]. Over the past two decades, there has been a notable shift towards adopting LCA as the preferred method, particularly within the maritime sector. For example, already in works of Shama et al. (2004)[89], the potential and related method of LCA for assessing ships was highlighted. This momentum gained further traction with the standardization[11] of LCA practices and its application across various product categories. Comparability of lifecycle performance of products within industries has further intensified the focus on using standardized LCA.

This preference for LCA as framework for lifecycle sustainability assessments, was also identified in a review paper by Mondello et al. (2021) [14]. Among these studies, LCC is typically used in addition when an interest exists in performing economic assessments. Literature is mainly focused on the operational phase of the vessel or other individual lifecycle phases[14]. A limited number of authors made attempts to develop a more holistic approach. Ling-Chin et al. (2016) [54] attempted to make a framework for LCA of marine photovoltaic systems. No research was found providing a comprehensive LCA method in the maritime industry. Scope and FU are left to the practitioner of the study, making comparison of different performed studies difficult[88].

Besides the review of Mondello et al. focusing on operational phases or other individual lifecycle phases, also coupled to economical concerns. A second literature review has been performed by Mio et al. (2022) [90][91]. Besides reviewing the use of LCA in the naval sector, a recommendation for normalization of earlier performed LCA outcomes is given, leading to standardized results which are better comparable industry wide and improve the reliability. In this review multiple outcomes of performed LCA studies on vessels that have been performed are compared, which gives a good indication of the large variations in outcomes of LCA analyses. Normalized outcomes from LCA's for cargo vessels are shown in figure 3.10.

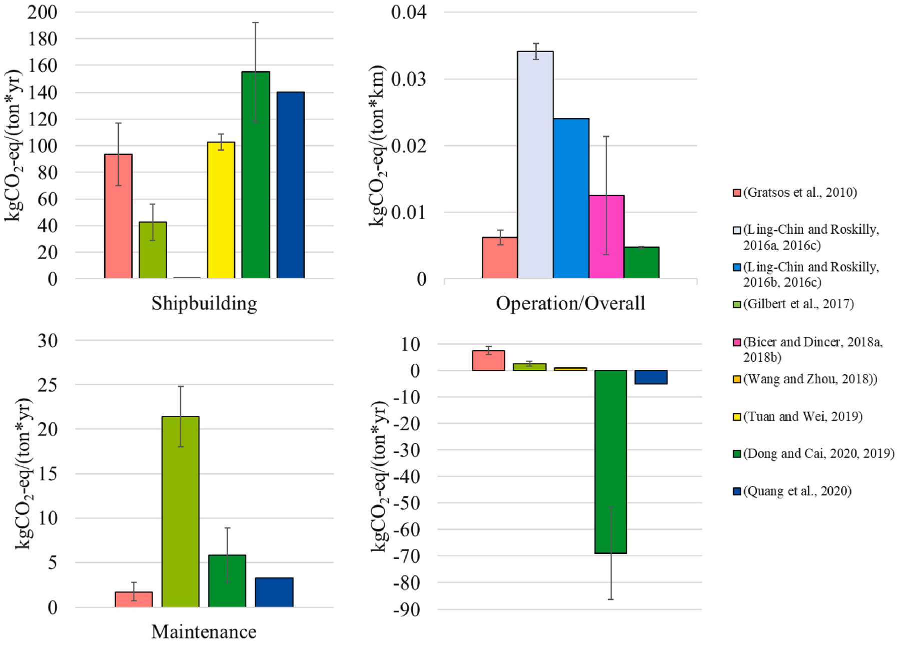


Figure 3.10: GHG-related normalized scores for Cargo Vessels. Error bars are reported when multiple outcomes, e.g., sensitivity analyses or different vessel configurations, have been evaluated by the original authors. Retrieved from Mio et al. (2022) [90]

3.2.1. Performed lifecycle sustainability assessments

Different studies about the design phase focus on the environmental impacts attributed to the hull structure, and the effects of designing heavier or lighter ships[92]. Although sometimes limited to certain lifecycle phases, earlier performed LCA show a significant environmental impact of construction and end-of-life phases of ships [36]. Different studies focusing on only subsystems of vessels have also been performed. In a hull subsystem assessment performed by [48], 90% of CO2 emissions of a Panamax tanker hull are found to be attributed to steel production processes within shipbuilding. In the total lifecycle phase of the hull, the impacts of shipbuilding, recycling, and maintenance are comparable.

A 2010 report issued by the OECD [16] suggests a general resistance from the shipbuilding industry, ship operators, and ship recyclers against performing lifecycle assessments, mainly because it requires the traditional industry of looking beyond their own industrial activity boundaries to unknown impacts.

3.2.2. Comparison and tradeoff

A wide range of sustainability assessment methods have been discussed. Different models have been made mapping different sustainability assessment methods, including the CapSEM model. The CapSEM model (Capacity Building in Sustainability and Environmental Management model) was developed to identify different levels on the pathway of reaching systemic sustainability [93]. It is proposed as a toolbox and guidance for organizations to help investigating which actions could be taken to improve environmental performance. The approach includes various methods[94] on different levels. These methods include both quantitative and qualitative tools, ranging from Input-Output analysis and LCA to corporate social responsibility (CSR) strategies, material flow analysis (MFA), Industrial Ecology (IE), and principles of Systems Engineering (SE). The four levels of the CapSEM model are visualized in figure 3.11. The four levels build upon each other, where every higher level represents a more mature sustainability development of a company. In the figure, for every level, a limited number of examples of methods are given.

The CapSEM performance and systemic scope as identified in the CapSEM model can be used in the evaluation of the discussed methods. The first level represent production process change, achieved by implementing Input-Ouput analysis or cleaner production. Increasing the systematic and performance scope, a product and value chain change is achieved at level 2 by implementing methods aimed at improving product sustainability like LCA. At level 3 organizational change is aimed for, by implementing more management wide pathways leading more sustainable business operations. The last level on the pathway to sustainability is systems change, where frameworks as Industrial Ecology, Material Flow Analysis represent the complete integration of material and energy flows within a company and its products produced.

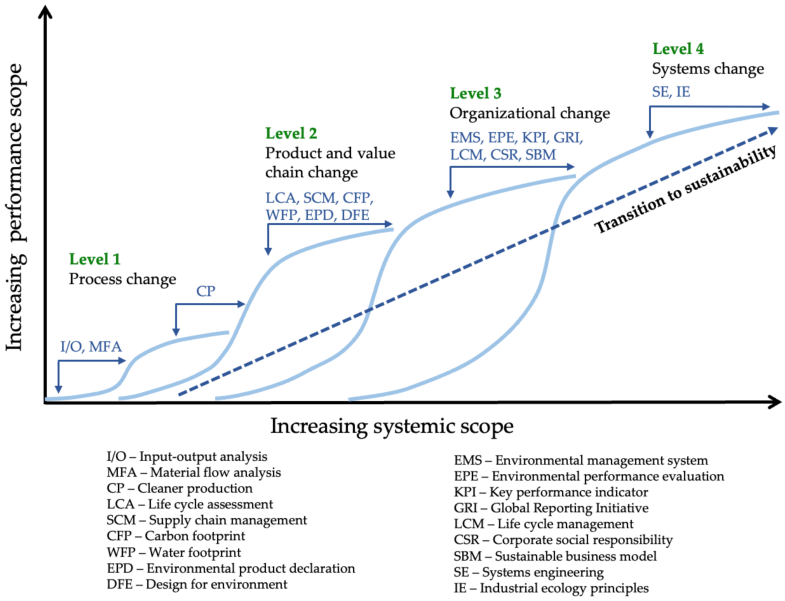
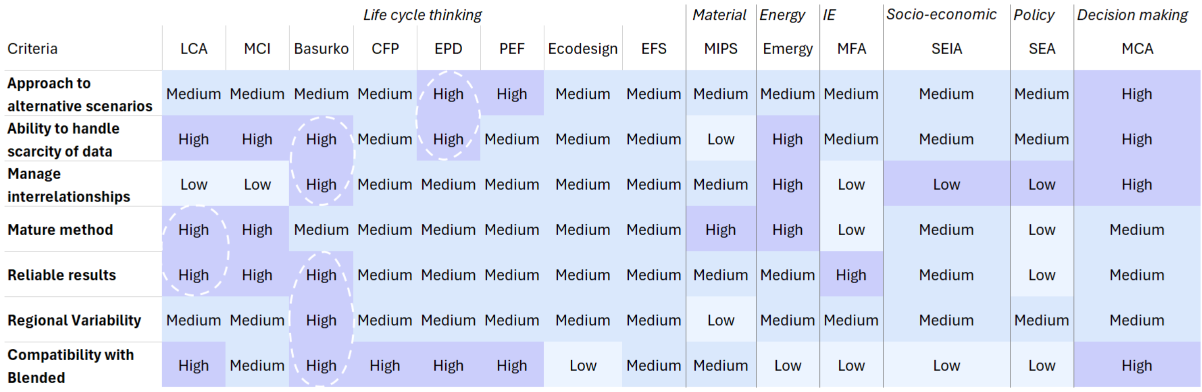


Figure 3.11: CapSEM levels, from Fet et al. (2021)[93]

Looking at the CapSEM levels, a distinction in the found frameworks can be made leading assessing the relevance of the method in the considered situation. In the case of *UDSBV*, the product value chain performance is targeted and conscious product development is desired. As level 2 methods include products and all related activities and processes, level 2 methods gather data for level 3 organizational management and strategies. To evaluate products and address key performance indicators level 2 method needs to be implemented.

With the criteria found in Chapter 2, the different level 2 methods found can be evaluated. In figure 3.12 this evaluation is shown. In this figure, 'Low' indicates partial fulfillment of the corresponding criterion, 'Medium' signifies moderate fulfillment, and 'High' indicates strong fulfillment. Based on this figure, a clearer understanding of the performance of the different methods can be gained. LCA is a mature method compatible with *Blended*, as GHG-emissions as performance indicators are part of LCA assessments. The LCA based Basurko method, specifically developed for marine problems, has an overall better score according to the criteria. Both EPD and PEF score better when an approach for different scenarios is desired, as the addition of product specific calculation rules ensures better comparability in different scenarios.



	Life cycle thinking								Material	Energy	IE	Socio-economic	Policy	Decision making
Criteria	LCA	MCI	Basurko	CFP	EPD	PEF	Ecodesign	EFS	MIPS	Emergy	MFA	SEIA	SEA	MCA
Approach to alternative scenarios	Medium	Medium	Medium	Medium	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High
Ability to handle scarcity of data	High	High	High	Medium	High	Medium	Medium	Medium	Low	High	Medium	Medium	Medium	High
Manage interrelationships	Low	Low	High	Medium	Medium	Medium	Medium	Medium	Medium	High	Low	Low	Low	High
Mature method	High	High	Medium	Medium	Medium	Medium	Medium	Medium	High	High	Low	Medium	Low	Medium
Reliable results	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Medium	Low	Medium
Regional Variability	Medium	Medium	High	Medium	Medium	Medium	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
Compatibility with Blended	High	Medium	High	High	High	High	Low	Medium	Medium	Low	Low	Low	Low	High

Figure 3.12: Comparison of sustainability assessment methods, the highlighted combination of LCA, Basurko and EPD complement eachother

3.3. Conclusion

A fusion is proposed of LCA with the recommendations of Basurko[35], EPD, and *Blended*. Basurko's proposition is tailored for addressing marine-specific issues in LCA, while EPD's Product Category Rules provide a framework for clearer scenario comparisons and design evaluations. By including the Index of Environmental Sustainability from Basurko's proposition and integrating these with the existing framework in *Blended*, the proposed fusion would facilitate trade-offs between different vessel designs. Considering the performance of the different approaches as evaluated in Figure 3.12, the combination of LCA, Basurko, and EPD would ensure maximal performance of the new sustainability assessment approach to be developed. As the approaches are all based on life cycle thinking, mutual compatibility between the approaches is ensured. Building upon these methods, a novel approach is suggested that combines the strengths of Basurko's LCA, EPD, and *Blended*. By harmonizing these three elements, designers could develop offshore vessels that are not only economically viable but also environmentally sustainable. Such an approach holds promise for meeting the demands of the modern maritime industry while contributing to global efforts to reduce greenhouse gas emissions.

However, it's crucial to acknowledge that these methods provide a general approach and necessitate customization to align with specific contexts or requirements. This customization is consistent with *Blended*'s current adaptability to specific contexts. Moreover, maintaining the new approach in accordance with LCA standards establishes a clear pathway for future extensions and conformity with potential regulations based on LCA standards. Rigorous testing and analysis are paramount to validate any new approach and ensure its effectiveness.

4
Method

A structured method would lead to good credibility of the calculation and provides a framework for later expansion, if desired as result of regulatory or further voluntary initiatives. In this chapter, a new method will be proposed, setting out the path towards answering the research questions earlier established.

4.1. LCA tools

Before introducing and proposing the new method that will be introduced and further investigated, a short overview is given of existing tools and methods for practical implementation of life cycle assessments. Different of these LCA tools exist, aiming at users looking for a plug and play lifecycle assessment software. These tools would include data, eliminating the users time of gathering data and developing handling tool performing an assessment. When data is available, a tool can be made without the need of already developed software[95].

One fundamental distinction among three impact assessment tools lies in their approach: the CML2001 and EDIP97 methods adopt a problem-oriented perspective, whereas the Eco-indicator 99 method follows a damage-oriented approach [35]. This difference dictates their modeling focus: while the former two methods assess impacts at a midpoint within the environmental mechanism between emissions and damages, the latter method concentrates on modeling damage to specific protection areas, including human health, natural and manmade environments, and natural resources. In an earlier performed LCA on vessels, CML2001 was used as tool [44]. However, in the research by Basurko[35], Eco-Indicator99 is used. For the case of *UDSBV*, where the focus is in the GHG-emissions, the use of a problem-oriented approach seems more implementable with with *Blended*, as the quantification of GHG-emissions is the desired performance indicator.

Ecoindicator99

Eco-indicator 99 utilizes a damage-oriented approach in LCA. The method's development commenced with the formulation of a weighting procedure, recognizing the challenge of assigning meaningful weights to numerous and abstract impact categories typical in LCA, such as acidification and ecotoxicity. Rather than directly weighting these impact categories, the focus shifted to assessing the severity of the damages they cause. To streamline the assessment process, the number of items to be evaluated was limited[96]. A panel comprising 365 individuals from a Swiss LCA interest group was tasked with evaluating the seriousness of three damage categories: Damage to Human Health, quantified as Disability Adjusted Life Years (DALYs); Damage to Ecosystem Quality, measured by the loss of species over a specific area and time period; and Damage to Resources, expressed as the surplus energy required for future extractions of minerals and fossil fuels. This approach aimed to provide a more targeted and actionable assessment framework for environmental impact evaluation[96].

CML

In the CML method, substances are often grouped or represented by sum parameters due to the lack of detailed emissions data in certain processes. This grouping is necessary because emissions are commonly specified collectively, such as aromatic hydrocarbons, which can vary significantly in environmental impact among individual substances within the group, rendering the resulting effect score somewhat unreliable. Regarding the Global Warming Potential (GWP), which measures a substance's contribution to the greenhouse effect, values are calculated over different time periods, considering substances' decomposition rates. For CML 1992, the GWP over a 100-year period is utilized, as it's the standard choice. Additionally, specific values for substances like CFC (hard) and CFC (soft) have been incorporated into the method to account for uncertainties in released CFC types[96]. The calculation of the greenhouse effect score per substance involves multiplying the GWP over 100 years by the airborne emissions in kilograms.

ReCiPe

ReCiPe, succeeding the Eco-indicator 99 and CML methods, was developed with the aim of merging the 'problem-oriented approach' of CML-IA and the 'damage-oriented approach' of Eco-indicator 99[96]. The former defines impact categories at a midpoint level, resulting in relatively low uncertainty in results but yielding numerous categories, complicating result interpretation. Conversely, the latter's damage-oriented approach simplifies interpretation with only three impact categories but entails higher result uncertainty. ReCiPe integrates both strategies, featuring both midpoint (problem-oriented) and endpoint (damage-oriented) impact categories. Midpoint characterization factors are multiplied by damage factors to derive endpoint characterization values, providing a comprehensive approach to impact assessment[96].

Remarks

The methods discussed above provide valuable insights, but directly applying them within *Blended* is not straightforward. Each method—CML, Eco-indicator 99, and ReCiPe—has its strengths, but they often require specific data structures or assessment focuses that do not align perfectly with the goals of *Blended*, particularly in optimizing vessel performance based on GHG emissions.

For *UDSBV*, where the primary focus is on greenhouse gas (GHG) emissions, a problem-oriented approach like CML is suitable, as it directly quantifies GHG outputs. However, to fully integrate into *Blended*, a new method will be coded specifically to work with the tool's outputs and structure. While methods like ReCiPe or Eco-indicator 99 could offer more comprehensive assessments, they cannot be directly implemented without significant adaptation.

Therefore, the custom-built method for *Blended* will focus on the specific lifecycle phases and emission types relevant to the tool, ensuring it aligns optimally with the operational and environmental performance metrics being used. Besides, a method is preferred that stays within the scope and timeframe set for this research to be completed in. This approach ensures that the tool remains efficient, reliable, and adaptable to the needs of the maritime industry, without the complexity or overhead of trying to fit in generic LCA methods.

4.2. New approach

A new approach is suggested, combining and materializing the strengths of different methods. As a basis the framework of Basurko's life cycle assessment for marine technologies will be used, where a LCA according to ISO 14040 will function as the sustainability assessment, in order to increase comparability PCR and normalization steps will be added and clarified. As the focus of this research is on what to calculate, opposed to processes like charaterisation, classification or normalisation, the aimed LCA method can be classified as 'Fast Track' LCA [97]. A small economic LCC indicator will be added in order to align the approach with the *Blended Design* tool. Different steps need to be taken to perform this combined life cycle sustainability assessment. In this section the different steps will be discussed in more detail.

Step 1. Define the scope of the study (scope)

Evaluating the sustainability of a technology implies a multifaceted process. Numerous factors come into play, each contributing to the overall assessment of sustainability throughout the technology's entire life cycle. In order to achieve the most reliable possible assessment, an approach would be required which evaluates every parameter, procedure or system within the vessel. Besides, a main goal of the approach in the case of *UDSBV* is facilitating comparability. This would allow for a trade off between different designs based on the assessed life cycle performances. This could be different sizes of ships, with different steel weights, different life cycle durations, or, as was researched by Peeten [32], the use of different energy systems on board. The first step of any lifecycle approach therefore should be the definition of the objectives that need to be achieved my implementation of the new approach. This

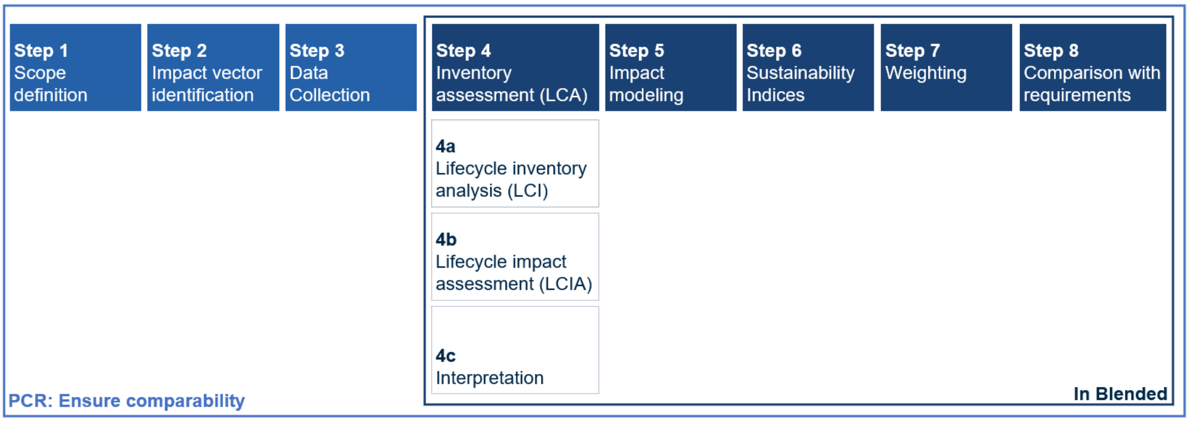


Figure 4.1: Proposed LCA approach to be implemented in Blended. Methodological adapted from Basurko [35], ISO1404[11] and ISO14025[67]. These steps will be programmed in *Blended*'s Python code, enabling a life cycle sustainability evaluation.

scope should describe the boundaries, limitations and assumptions that are to be considered within the assessment.

Step 2. Identification of impact vectors

The second step involves a comprehensive analysis of each technology or system from a life cycle standpoint. This analysis is crucial for several reasons. Firstly, it allows for the identification of various vectors encompassing both variables and parameters, which might have influence on the environment. Secondly, it enables the estimation of potential additional costs that could arise throughout the entire life cycle period. By undertaking this analysis, designers can gain valuable insights to optimize their designs for sustainability, safety, and cost-effectiveness in offshore operations. The impact vectors which are analyzed should ideally match the performance indicators in *Blended*, in order to ensure compatibility.

Step 3. Data collection (inventory)

Thirdly, data collection is needed for the vectors identified in the previous step. This data should be as complete as possible, to ensure the best possible assessment. In some cases estimations and generalizations should be made when data is lacking. This step should be inline with Product Calculation Rules as used in EPD, in order to ensure comparability among different designs within *Blended*.

Step 4. Assessment of inventory (assessment) > LCA

After the data collection, evaluation by using impact assessment methods will be performed. As follows from the trade of in the previous chapter, LCA will be used for the environmental impact assessment, and the highly compatible LCC will be used to add the economic dimension to the assessment, as was proposed by Basurko [35].

Step 4a LCI

Inventory analysis entails gathering and calculating data to measure the inputs and outputs of a product system. It's an iterative process where as more data is collected and system understanding deepens, adjustments to data collection methods may be needed to meet study goals[11]. Additionally, issues may arise necessitating revisions to the study's objectives or scope.

For each process and part of the vessel design all data will be organized. This will be done in line with the set up PCR, with similar units and expressions. Examples of headings as specified in ISO14040 are[11]: energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products and waste, emissions to air.

Step 4b LCIA

In the impact assessment phase, the LCI results will be used to determine the significance of potential environmental impacts. This entails attributing the data fro the inventory with specific environmental impacts and indicators. In the case of *UDSBV*, the main impact category indicator is Global Warming Potential by assessing the GHG-emission impacts of different vessel designs. The information following from the LCIA will be interpreted in the following step. The impact assessment might involve iteratively reviewing the goal and scope of the LCA study to assess whether the study's objectives have been achieved, or to adjust the goal and scope if the assessment suggests that they are unattainable [11].

The division of the LCIA phase into separate elements is both beneficial and necessary for several reasons[11]. Firstly, each LCIA element possesses certain characteristics that can be clearly defined, aiding in their individual analysis. Secondly, during the goal and scope definition phase of an LCA, considering each LCIA element separately allows for a more precise delineation of objectives. Thirdly, conducting a quality assessment of the LCIA methods, assumptions, and decisions for each element enhances overall accuracy and reliability. Fourthly, separating LCIA procedures and assumptions within each element promotes transparency, facilitating critical review and reporting. Lastly, by transparently disclosing values and subjectivity within each element, termed as value-choices, critical evaluation and reporting can be effectively conducted.

Step 4c Interpretation

Interpretation in LCA involves combining findings from inventory analysis and impact assessment to produce results consistent with the study's defined goals and scope. It aims to offer conclusions, address limitations, and provide recommendations, considering the relative nature of LCIA results and their indication of potential environmental effects rather than actual impacts[11]. Interpretations, presented as conclusions and recommendations, should cater to decision-makers and ensure a clear, comprehensive presentation of LCA results while allowing for iterative refinement of the study's scope and data quality. Ultimately, the interpretation phase should reflect the evaluation element's outcomes.

Step 5. Environmental, economic and social impact modelling

As both data collection and impact assessments are considered to be very time consuming practices, Basurko[35] proposes to create estimation models. Developing estimation models offers a structured approach to streamline sustainability studies, consequently cutting down the time needed to generate unforeseen scenarios. The outcomes of these assessments can be used to formulate mathematical models related to pollution and expenses. In earlier research performed as part of the research of Basurko[35], it is proposed to use intelligent algorithms to produce the desired estimation models. These models would be particularly relevant when the scale of the assessment and the volume of data to be collected pose limitations in conducting the evaluation.

Step 6. Sustainability indices

The outcomes derived from either the assessment or modeling can offer insights into the sustainability performance of a particular dimension, enabling comparisons across different results within that specific aspect. However, before analysis, these results must undergo normalization based on legislative constraints, thresholds, or benchmark limits, leading to numerical outputs. Three sustainability indices emerge from this process: the Environmental Sustainability Index, the Economic Sustainability Index, and the Social Sustainability Index. From which the last is out of scope in this research.

The desired impact categories are determined based on the current performance indicators in *Blended*. Normalization factors are usually used in the normalization process, as described by Tugnoli et al. (2008)[98]. As only GHG-emissions are considered in this research, there is no need of finding a single scores method combining different types of environmental impacts. However, normalization and assigning an index of environmental sustainability is useful in the trade off between different designs. The choice can be made to apply weighting to impact categories to incorporate factors such as long-term effects into their analysis. While it is generally advisable to avoid weighting[35], a set of weighting factors may be applied to the normalize the results. This could for example be beneficial when taking into account the long term development of steel production emissions and scrap steel use.

For the *Blended* case, where a comparison is desired between generated designs, the sustainability index itself can be non-dimensionalized, in order to create scores for the performance of every vessel. For example: If 1000 vessel designs would be considered, the solution with the lowest environmental impact could be assigned score 0, representing the most 'environmentally friendly option', while 1000 represents the least environmentally sustainable option. The highest value obtained during the comparison could be regarded as the maximum score, set at 1000; consequently, the remaining data could be normalized accordingly.

Step 7. Weighting

In the weighting step the obtained index of environmental sustainability can be weighted according to legislative or political priorities, to test if the found designs comply with all requirements[35]. It's important to highlight that in accordance with ISO 14044, LCA includes an optional stage referred to as "weighting." During this phase, impact categories can be assigned weights based on the study's objectives and scope. This weighting process is specifically inherent to the LCA study and Step 4 [11].

Step 8. Comparison with the established requirements (multi criteria decision-making)

In the last step decision making takes place based on the set requirements and comparison of generated designs. This will ultimately lead to the selection of the design which aligns best with the clients expectations. This step is already part of the *Blended* process, and is as such not a new addition.

4.2.1. Comparability

In evaluating numerous designs generated by *Blended*, the ability to compare different assessments is crucial for making informed decisions on the optimal choice. Comparing assessments allows for a comprehensive analysis of each design's strengths and weaknesses across various criteria, such as functionality, cost-effectiveness, and sustainability. By conducting comparative assessments, decision-makers gain valuable insights into the trade-offs inherent in each design, enabling them to identify the most promising options. Moreover, comparing assessments facilitates the identification of common trends or patterns among designs, which can inform iterative improvements and refinements. Ultimately, the ability to compare different assessments empowers decision-makers to select the design that best aligns with their objectives, maximizing the likelihood of success and innovation in the design process.

Incorporating product calculation rules (PCR) enhances the effectiveness of comparing assessments of different designs and alternative scenarios. These rules provide standardized metrics and criteria for evaluating the performance of each design, ensuring consistency and reliability in the assessment process[67]. By adhering to established product calculation rules, such as those based on industry standards or regulatory requirements, decision-makers can accurately quantify and compare key aspects of each design, such as environmental impact, cost efficiency, and safety. Making use of product calculation rules enhances the comparability of assessments between different designs, enabling more confident and effective decision-making.

4.2.2. Sensitivity Analysis

Incorporating a sensitivity analysis of the LCA results into the design tool would offer several notable advantages. Firstly, it would enhance the robustness and reliability of the assessment by systematically exploring the impact of variations or uncertainties in input parameters on the final outcomes [99]. The addition of this analysis is also recommended in ISO14042[11]. This would provide stakeholders with valuable insights into the sensitivity of the results to different assumptions or data inputs, enabling a more informed decision-making process. Additionally, conducting a sensitivity analysis can help identify critical factors that significantly influence the outcomes, allowing for targeted efforts to improve data accuracy or prioritize areas for further investigation. Ultimately, the inclusion of a sensitivity analysis would improve the credibility and usefulness of the LCA results, facilitating more effective and defensible decision-making in the design of environmentally sustainable ships.

4.3. Method Summary and Outlook

The proposed life cycle sustainability assessment (LCSA) approach, adapted from established LCA frameworks and methodologies such as those of Basurko and ISO 14040, sets a structured pathway to integrate environmental, economic, and lifecycle performance into early-stage ship design. By aligning this approach with the *Blended Design* tool, it will allow a detailed assessment of GHG emissions, construction impacts, and operational performance.

With the detailed scope and method in place, the next step will involve outlining the specific data inputs and programming structures necessary to implement this LCSA approach within *Blended*. Ultimately, this approach will enable designers to optimize vessel designs not only based on operational efficiency but also based on their full lifecycle environmental and economic impacts.

This chapter aimed to answers research questions 2 and 3. In the following chapters, the scope of the study will be outlined, followed by detailed data collection, programming, and tool development. Together, these steps will allow for a comprehensive lifecycle assessment, addressing the remaining research questions and laying the foundation for innovative ship design choices.

5

Compatibility and Scoping

As a first step, creating a comprehensive and detailed scope is crucial for the implementation of a new LCA approach in *Blended*. The purpose of this scope is to provide a clear understanding of the level of detail and perspective from which the life cycle assessment will be performed, as well as to outline the requirements for the data needed to conduct the assessments. This is needed as first step in answering the research questions and corresponds with **Step 1** and **2** as defined in the new approach in chapter 4.

5.1. Compatibility

Blended includes the environmental performance of the vessel during operations. This performance is expressed in CO2 emissions, which are subsequently transformed into an EEXI index. Within the overall scope of this research, these operational CO2 emissions will be complemented by the CO2 emissions from other phases of the ship's lifecycle. To expand *Blended* with the suggested approach, which will quantify the CO2 equivalent impacts of all lifecycle phases, a clear scope and defined expectations for the procedure and anticipated outcomes are necessary. *Blended* currently expresses CO2 in **tonnes** or **grams**, using these measurements to calculate the EEXI by dividing the CO2 emissions in grams by the transportation work, which is the cargo multiplied by the distance, given in **metric tonne nautical miles**.

5.2. Focus

As shown in earlier parts of this research, different phases of the lifecycle have varying levels of impact on the overall CO2 footprint. Notably, the end-of-life phase can have a low or even negative environmental impact, depending on how scrapping and recycling are conducted. According to the literature, construction has the largest CO2 emissions outside of operational performance. The expansion of *Blended* will primarily focus on vessel construction and maintenance. Both phases involve significant steelwork, which, as earlier research indicates, generates considerable CO2 emissions. The impacts of end-of-life processes and design considerations are expected to be comparatively limited.

In an earlier mention study performed by Gilbert et al. (2017) [15] the CO2 emissions of the hull subsystem of a Maersk Line 'Triple-E' are quantified. When regarding the construction phase of the vessel, this research can provide valuable insights into the most significant sources of CO2 emissions during construction. Figure 5.1 shows the CO2 emissions from the hull subsystem, along with the percentage contributions of the various analyzed processes. For 'Birth', which is used to denote the conversion and processing of raw materials into materials used during construction of the vessel, the raw material production stands out as the overall biggest source of emissions for the complete hull lifecycle. The impact of steel transportation, from the steel production plant in China to the shipyard in Korea is limited to around 0,5% of hull lifecycle emissions. For 'Manufacturing', the phase where the vessel is constructed, welding and sandblasting of the vessel account for 9.42% and 1.71% respectively. In the study of Gilbert et al. painting, anode protection and steel cutting all have a limited contribution to the overall CO2 emissions. During the maintenance phase, addition steel, reinforcements of welds and hull cleaning have significant contributions to the emissions. Gilbert accounted for ship breaking an recycling, and accounts for the additional transport efforts for the recyclable material. For the hull subsystem, the components identified by Gilbert et al. and by Ulstein Verft AS in Norway as having a significant environmental impact will be included. These components notably include painting and cutting, as Ulstein Verft AS estimates these processes contribute more substantially to overall emissions. In cases where differing assessments of impact significance exist, they will be considered and evaluated in the later stages of the analysis.

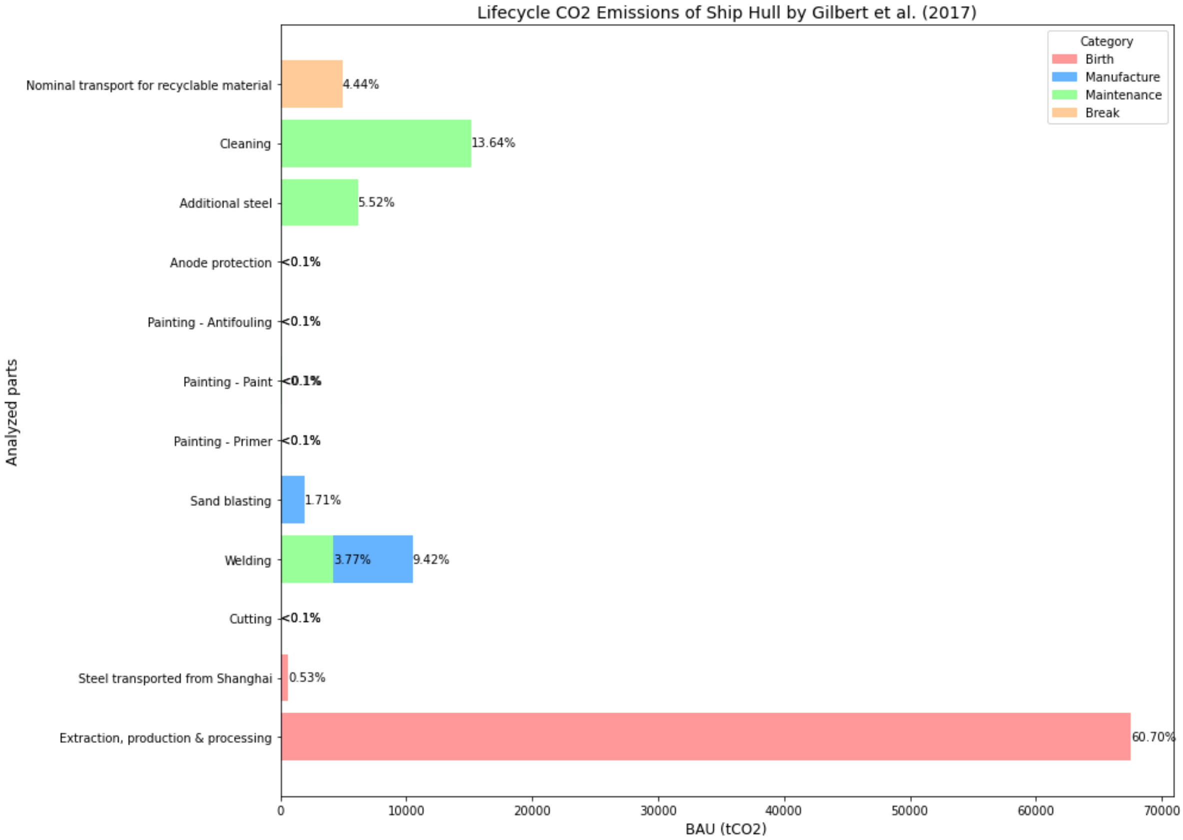


Figure 5.1: Environmental impacts and percentages of parts of the Hull subsystem

5.2.1. Heavy transport vessel

As mentioned earlier in this report with the HX121, other vessel types designed using *Blended*, such as Subsea Rock Installation (SRI) vessels or Wind Turbine Installation Vessels (WTIV), will require further expansion of the tool beyond the relatively straightforward Heavy Transport Vessel (HTV). Future enhancements of the LCA module to include SRI and WTIV vessels have been considered during the tool's development. The coding is designed to be flexible and compatible with other parts of *Blended*, allowing for the easy addition of columns in dataframes to accommodate new data as needed.As mentioned earlier in this report with the HX121, other vessel types designed using *Blended*, such as Subsea Rock Installation (SRI) vessels or Wind Turbine Installation Vessels (WTIV), will require further expansion of the tool beyond the relatively straightforward Heavy Transport Vessel (HTV). Future enhancements of the LCA module to include SRI and WTIV vessels have been considered during the tool's development. The coding is designed to be flexible and compatible with other parts of *Blended*, and allows for the easy addition of columns in dataframes to accommodate new data as needed.

Figure 5.2: ULSTEIN HX121 Heavy transport vessel

5.3. Impact Vector determination

The impacts in this research will be quantified in tonnes of CO_2-equivalent. By evaluating CO_2 emissions at each stage of the vessel's lifecycle, a comprehensive CO_2 score can be determined for the vessel's overall lifecycle impact. This approach ensures that all contributing factors—from material extraction and production to maintenance and disposal—are systematically accounted for and expressed in CO_2 terms. This enables a clear and holistic understanding of the vessel's environmental footprint. Alignment with the previously implemented EEXI module will be further explored, as this will require emissions to be expressed in CO_2/tonne-Nm. This index will build on earlier calculations done in CO_2 equivalents.

5.4. Processes within the scope

In this section, the key processes that will be integrated into the *Blended* tool are outlined. These processes build on the research and observations discussed previously, covering the full lifecycle of a vessel—from material sourcing and construction to operation, maintenance, and end-of-life disposal. Each process is expected to play a role in contributing to the vessel's overall CO_2 emissions, and by coding these into *Blended*, a comprehensive assessment of the vessel's environmental impact can be generated. Figure 5.3 illustrates the various lifecycle stages and their corresponding processes which are within the scope of this research. In the following subsections, these processes and the unit requirements for the data to be collected will be further discussed.

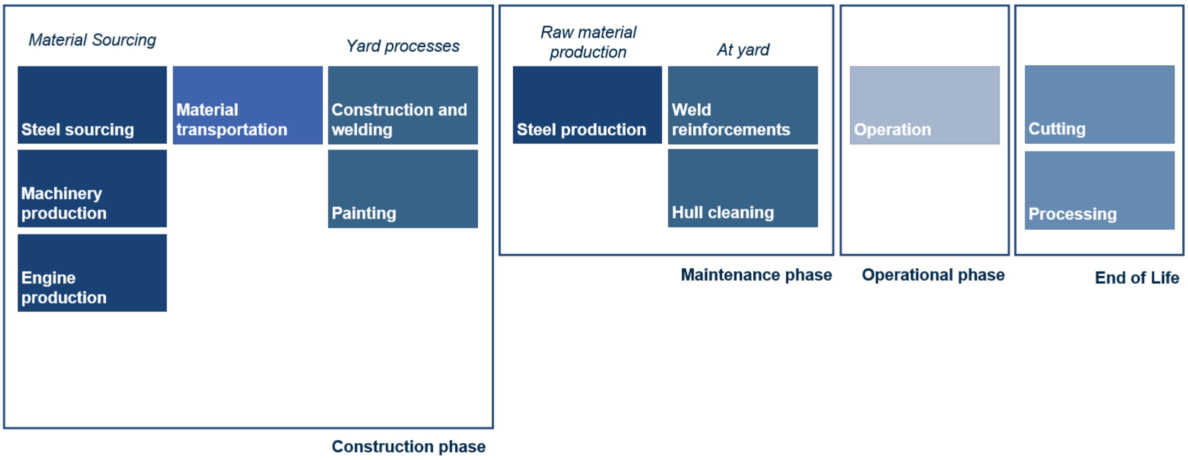


Figure 5.3: Processes within the scope of the research

5.4.1. Construction phase

Emissions are associated with various stages of vessel construction. To achieve a comprehensive lifecycle emission assessment, CO_2 emissions must be attributed to each part of vessel construction.

In *Blended*, estimations are made for a range of weights that contribute to the vessel's lightship weight, serving as key indicators of the various parts involved in the vessel's construction.

Steel sourcing

The *Blended* tool produces a lightship weight estimate. This weight estimation is split up in several parts, being:

- Hull
- Superstructure
- Crew equipment
- Engine
- Machinery systems

These weights are based on scaling functions, as was described in the research of Zwaginga et al. (2021) [34]. For every weight, a corresponding CO2 impact could be attributed. Besides, different other parts of the construction can be attributed CO_2 emissions. The main processes defined in studies by Johnsen et al. [100], Cucinotta et al. **2020** and Gilbert et al. [15] are hull cutting, hull sandblasting, welding and painting.

Steel Sourcing

The production of steel from raw materials has a significant environmental impact [101]. This impact can vary based on the location of steel production, as different production methods are used in different regions. In *Blended*, this variability can be accounted for by weighting the impacts accordingly. Incorporating various production methods and their related emissions allows for an investigation into the effect of different building locations on lifecycle CO2 emissions. This is achieved by including the carbon intensity of steel production at different locations, each with its respective CO2 intensity. This impact should be expressed in **tonnes CO2/tonne steel**.

Distance Between Yard and Location of Steel Production

Transporting steel from its production site to the shipyard also generates CO_2 emissions, which are considered in *Blended* by weighting the transport impacts. This analysis can utilize standardized average distances based on the location of shipyards to streamline the calculation process. For example, standard distances from major steel production centers to common shipbuilding yards can be used to estimate transportation emissions more generally. Within the scope of this research, both land- and sea-based transport will be factored in, depending on the different geographic location of steel sourcing used. These emissions will be expressed as **tonnes CO_2/tonne steel transported**.

Hull Construction

The hull construction phase is a critical component of shipbuilding, involving the assembly of various steel parts to form the main structure of the vessel. This process includes several activities such as cutting, welding, and shaping steel plates, each contributing to the overall CO2 emissions. Among these activities, welding is expected to account for significant impacts due to its energy-intensive nature [15]. As seen in earlier research, the environmental impact of hull construction is predominantly driven by the emissions from welding.

To accurately capture the environmental impact, the emissions from constructing the hull from the delivered steel can be expressed in **tonnes CO2/tonne hull**. Based on estimates from literature for the amount of welding needed during the construction phase for a certain ship.

Machinery production and installation

The emissions from the process of production of equipment could be expressed using an average value for environmental impact per weight of equipment in **tonne CO2/tonne equipment**.

Exterior and interior painting

The process of applying coatings to the vessel during its construction phase has significant environmental implications, typically measured in terms of CO_2 emissions per unit area (**tonnes of CO_2 /sq m area painted**).

5.4.2. Maintenance phase

Over the course of its operational lifespan, various maintenance activities contribute to the overall CO_2 emissions of the vessel. In *Blended*, the emissions from the key maintenance processes are modeled based on the frequency and intensity of these interventions, with a particular focus on steelworks, weld reinforcements, and hull cleaning and recoating.

Steelworks

During routine maintenance, it is common for sections of the vessel's steel structure to be repaired or replaced due to wear, corrosion, or other damage. The emissions resulting from this steelwork are attributed to the amount of steel used during these maintenance activities. For each tonne of steel replaced or reinforced, the corresponding CO_2 emissions are calculated and expressed as **tonnes CO_2/tonne steel**. These emissions are added to the overall lifecycle emissions of the vessel and are based on the steel sourcing and processing impacts described during the construction phase.

Weld reinforcements

Over time, welds on the vessel can degrade, requiring reinforcement to maintain the vessel's structural integrity [15]. The energy-intensive nature of welding contributes significantly to the overall CO_2 emissions during maintenance. These emissions can be calculated based on the quantity of weld reinforcements applied, with emissions expressed in **tonnes CO_2/tonne of weld material**.

Hull cleaning and recoating

To ensure the vessel's hydrodynamic efficiency and protect the hull from corrosion, regular cleaning and recoating are essential maintenance activities. Hull cleaning typically involves sandblasting, which removes accumulated marine growth and old paint layers, while recoating applies a fresh layer of protective paint. Both processes contribute to the vessel's lifecycle emissions, and these emissions can be modeled in *Blended* based on the surface area of the hull that is cleaned and repainted. The emissions for welding and painting activities are expressed the same as for the emissions during the construction phase **tonnes CO_2/sq m exterior area**.

By accurately modeling these maintenance processes in *Blended*, a comprehensive view of the environmental impact during the vessel's operational lifespan is achieved, ensuring that all emissions—both from initial construction and ongoing maintenance—are captured and integrated into the vessel's overall CO_2 lifecycle assessment.

5.4.3. Operation

Blended incorporates a specialized module that accounts for the operational life of a vessel, quantifying its environmental impact using the Energy Efficiency Existing Ship Index (EEXI). This module is designed to assess how various operational factors, such as fuel consumption, emissions, and efficiency measures over the vessel's lifetime, contribute to its overall EEXI rating. For this research, an seperated module expressing the lifetime CO_2 emissions from operations will be added, expressed in **tonnes CO_2**.

5.4.4. End of Life

The CO_2 emissions associated with the end-of-life phase will be calculated based on the decommissioning and recycling processes. Two primary sources of emissions will be attributed:

Cutting

During decommissioning, the vessel will be dismantled, and the steel components will be cut into transportable sizes. The emissions from this activity will be attributed to the energy consumed during cutting operations. The cutting process typically involves cutting techniques which require significant energy inputs[15]. These emissions will be quantified using specific emission factors associated with the energy consumption per tonne of steel cut, and expressed in **tonnes CO_2/tonne steel cut**.

Processing

After the vessel is dismantled and the steel is cut into transportable pieces, these parts will be transported to recycling facilities or storage yards. The transport emissions will be calculated based on the distance from the shipyard to the final destination, typically recycling centers or backlands. These emissions will be divided into land and sea based transport.

CO_2 emissions will be estimated based on the number of truckloads required to transport the dismantled steel, the total distance traveled, and the emission factor for truck transport. These emissions will be expressed in **tonnes CO_2/tonne steel transported** of road transport. Similarily and expression will be found in **tonnes CO_2/tonne steel transported** for sea based transport. The transport emissions will be weighted by the distance to recycling facilities or processing plants, ensuring that both short and long-distance transport scenarios are captured. Standard or region-specific transport factors will be used, depending on the available data.

5.5. Accuracy of Data

To ensure the highest possible accuracy, data from multiple literature sources will be used whenever available. In situations where exact data is not known, data ranges can be created based on the available information. The uncertainty resulting from these ranges should be reflected in the results to clearly indicate the magnitude of uncertainty in the quantified impacts. An uncertainty analysis will be performed after the tool's implementation to validate its accuracy and relevance in ship design. Additionally, a study on the impact of data accuracy will be conducted following the tool's development.

5.6. Verification

The accuracy and reliability of the CO_2 emissions estimates can be verified using a dual approach: through a reference vessel from the literature and real-world calculations conducted simultaneously at the Ulstein yard in Norway. This comprehensive strategy ensures that the results align with industry standards and are grounded in practical shipbuilding data.

5.6.1. Reference Vessel Verification

The use of a reference vessel is already integrated into the *Blended* tool. This reference vessel serves as a benchmark, enabling the calculated emissions and scaling factors to be cross-checked against a vessel of similar type, size, and function that has been documented in existing literature. By using a reference vessel, the tool can validate both the accuracy and credibility of the weight estimates and lifecycle emissions provided by *Blended*. Building on previous work by Zwaginga (2021) [34], Peeten (2022) [32], and de Ridder (2023) [57], the results produced by the *Blended* tool are considered reliable. Furthermore, by including a reference vessel with known environmental impacts, the lifecycle emissions calculations can be cross-validated to ensure precision.

The reference vessel data should include key parameters such as tonnage, dimensions, operational profile, and construction methods. These provide the foundation for validating both the construction and operational emissions of the vessel under study. By comparing the emissions from specific components—such as steel production, hull construction, and machinery installation—directly with those of the reference vessel, consistency and accuracy can be ensured.

Reference Calculations at Ulstein Yard

real-world data from shipbuilding processes at Ulstein yard in Norway offers another layer of verification. These reference calculations involve real data on material usage, energy consumption, and logistics operations during the shipbuilding process. By comparing the emissions calculated within *Blended* to those recorded during actual ship construction at Ulstein, the tool's accuracy can be evaluated in a practical and applied context.

Data from Ulstein yard, such as energy consumption per tonne of steel cut, emissions from welding processes, and transport distances for material delivery, provide comprehensive information for verifying *Blended*'s outputs. Ensuring alignment between these real-world metrics and the calculated impacts from *Blended* increases confidence in the tool's reliability.

5.6.2. Validation via Sensitivity Analysis

A sensitivity analysis will further verify the robustness of the *Blended* tool by assessing how variations in key input variables affect the overall CO_2 emissions. For instance, changes in steel production methods, transportation distances, or operational profiles can be simulated to determine whether the results remain consistent when compared to the reference vessel.

This approach ensures that the tool responds appropriately to changes in the input data and that its results are not overly sensitive to small variations in assumptions. By confirming that *Blended* produces stable and realistic results across different scenarios, the overall accuracy and reliability of the lifecycle impact calculations are strengthened.

5.7. Perspectives

Within LCA, three main perspectives can be identified, each representing a distinct viewpoint on how to assess environmental impacts and make decisions based on those assessments. These perspectives influence the handling of uncertainties and the selection of environmental indicators in the analysis[96]. The perspectives are:

Hierarchist Perspective: This perspective takes a long-term view, including substances in the assessment if there is a broad consensus on their effects. It assumes that environmental damages can be managed through proper practices and may exclude certain risks, such as the impact of rising sea levels. It also factors in the gradual substitution of fossil fuels[96].

Egalitarian Perspective: This perspective adopts an extremely long-term outlook, including substances if there is any indication of their effects, even if the data is uncertain. It assumes that damages are largely unavoidable and may lead to catastrophic consequences[96].

Individualist Perspective: This perspective focuses on the short term (100 years or less), considering only substances with definitive proof of their effects. It assumes that technological and economic development will mitigate environmental damages over time, and excludes certain potential risks[96].

Given the focus of this research on CO_2 equivalent emissions and the alignment with previous EEXI calculations, it follows logically that the hierarchist perspective will be applied. This perspective is the most compatible with the research goals, as it relies on well-established carbon intensities and widely accepted scientific consensus. The hierarchist approach ensures that the CO_2 equivalent emissions data to be gathered later in this study will fit seamlessly with the established framework used in *Blended*.

The proposed method in *Blended* focuses on calculating CO_2 equivalent emissions over the vessel's lifecycle, making the hierarchist perspective a natural choice. This perspective allows for a straightforward and efficient analysis, concentrating on quantifiable GHG impacts without broadening the scope to indirect or uncertain environmental effects. By focusing solely on CO_2 equivalent emissions, the analysis remains aligned with both the regulatory frameworks and the practical needs of the study.

Alternative perspectives, such as the egalitarian or individualist, would introduce unnecessary complexity. The egalitarian perspective would require expanding the assessment to include uncertain or indirect CO_2 effects, which would necessitate gathering additional, often unavailable, data. On the other hand, the individualist perspective, while focusing on short-term impacts, might overlook important long-term effects relevant to the lifecycle of the vessel. Both perspectives would likely complicate the analysis without adding significant value.

Thus, following the hierarchist perspective is both a logical and practical choice for this research. It ensures compatibility with previous work on EEXI in *Blended* and allows for a focused, efficient analysis of CO_2 equivalent emissions.

5.8. Conclusion

This chapter establishes a structured approach for expanding the *Blended* tool to perform lifecycle assessments (LCA) of heavy transport vessels. The outlined framework ensures that CO_2 emissions are accurately quantified and attributed across all key lifecycle stages—construction, operation, maintenance, and end-of-life. This comprehensive assessment allows for a clear understanding of the vessel's total environmental impact.

A specific focus was placed on the construction and maintenance phases, as these stages contribute significantly to the vessel's CO_2 emissions. The proposed methodology ensures compatibility with the operational performance metrics already in use within *Blended*, maintaining consistency in calculating CO_2 impacts throughout the vessel's lifecycle.

All units necessary for determining the impact vector—expressed in terms of CO_2 equivalents—have been identified and outlined for each lifecycle phase. This provides a solid foundation for calculating lifecycle emissions and supports further tool development. Additionally, the flexible design of the tool would allow for the integration of other vessel types, such as Subsea Rock Installation (SRI) and Wind Turbine Installation Vessels (WTIV). This adaptability enhances *Blended*'s use in facilitating more informed, data-driven decision-making for sustainable ship design and operation.

6

Data collection

The use of reliable data is of paramount importance to accurately perform a life cycle assessment. Reliable data ensures the precision and validity of the assessment outcomes, which are critical for making informed decisions about environmental impacts. Both literature sources and detailed lifecycle inventory analyses provide a solid foundation for such data. Specifically, data obtained from a comprehensive lifecycle inventory analysis conducted at Ulstein Verft in Norway offers valuable insights and empirical evidence. This data, coupled with relevant literature, forms the basis for the data used in expanding Blended. By integrating these data sources,the accuracy and credibility of the life cycle assessment can be enhanced, ultimately leading to more sustainable and well-informed practices.

6.1. Construction Data

Based on the identified processes within the ship's lifecycle, as outlined in the scope, specific data must be collected and attributed to each part of the construction phase. This data will form the basis for quantifying the CO_2 emissions associated with the construction of the vessel. The goal is to ensure that all relevant construction activities—ranging from material production to assembly—are accurately represented in terms of their environmental impacts, ultimately allowing for the calculation of the lifecycle emissions impact vector.

To achieve this, data sources for each of the construction processes must be identified. To ensure consistency with the previously determined impact vector, data that aligns with the units specified in the Scope and impact vector determination is preferred. If the available data does not directly match these units, appropriate calculations will be proposed to standardize the emissions data accordingly.

6.1.1. Steel sourcing

Based on the report by the joint research center of the EU commission (2022) [101], emission intensities for steel production from the EU and trading partners can be found. The steel sourcing for the ship considers the geographical carbon intensity variations for both Scope 1 (direct) and Scope 2 (indirect, e.g., electricity) emissions, as represented in the integrated route emissions data. The integrated route described in this report corresponds to the BF-BOF production route, which was previously identified as the preferred method of steel production for shipbuilding (chapter 2.1.2). The integrated route also represents the most common steel production in the countries researched, except USA and Türkiye. The following regional carbon intensities apply for steel produced via the integrated route (Scope 1 + upstream + Scope 2):

- **EU**: 1.81 tonnes CO_2/tonne steel
- **China**: 1.84 tonnes CO_2/tonne steel
- **Korea**: 2.0 tonnes CO_2/tonne steel
- **Taiwan**: 2.1 tonnes CO_2/tonne steel
- **United States**: 2.0 tonnes CO_2/tonne steel
- **Japan**: 1.95 tonnes CO_2/tonne steel
- **Turkey**: 2.5 tonnes CO_2/tonne steel
- **Brazil**: 1.9 tonnes CO_2/tonne steel

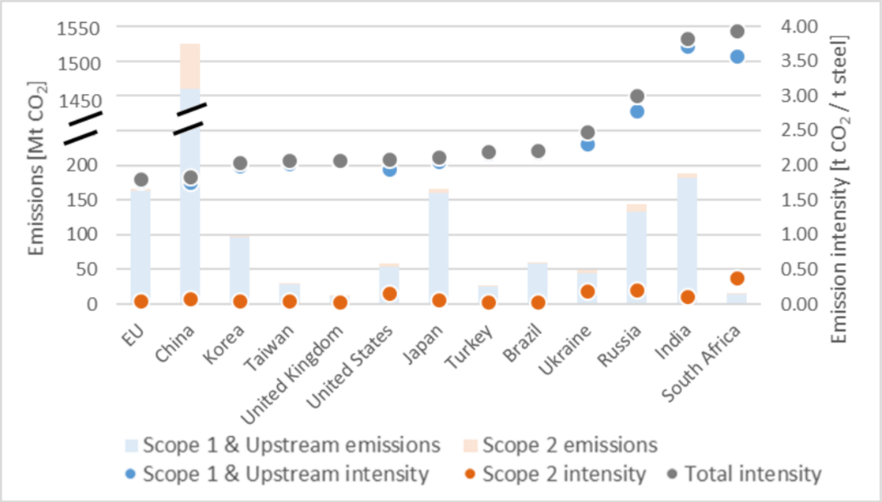


Figure 6.1: Carbon intensities of EU trading partners,from JRC(2024)[101]

- **Ukraine**: 2.3 tonnes CO_2/tonne steel
- **Russia**: 2.6 tonnes CO_2/tonne steel
- **India**: 3.8 tonnes CO_2/tonne steel
- **South Africa**: 3.9 tonnes CO_2/tonne steel

The lowest carbon intensities are reported in the EU and China, both under 1.85 tonnes CO_2 per tonne of steel. In contrast, countries such as India and South Africa exhibit the highest carbon intensities, with values exceeding 3.8 tonnes CO_2/tonne steel. This is significant when considering the environmental impact of steel sourcing based on its origin.

Additionally, Scope 2 emissions, which include electricity consumption, are particularly high in regions like South Africa due to the carbon-intensive nature of the electricity grid (990 g CO_2/kWh), whereas countries like Brazil benefit from hydroelectric power, reducing their Scope 2 emissions.

As most emissions are expected to come from steel production, and the concepts of *UDSBV* are meant to be constructed within a foreseeable future, the effect of the difference in carbon intensity in 20 years is limited to the steel added during maintenance. Therefore, a similar projection for carbon intensity reduction will be suggested for different countries, ultimately leading to low carbon steel in 2050. The future projections of this carbon intensity will be implemented for the steelworks during maintenance, where the effect of different carbon intensity projections can be studied.

For every 1.0 tonnes of steel used in the hull, an additional 0.1 tonnes can be assumed to be lost during the construction phase [100][102]. This loss accounts for inefficiencies and wastage during the assembly process. The emissions from these processes are added to the total lifecycle emissions for the vessel.

6.1.2. Steel construction

Based on the research done by Gilbert et al. 2017, the[15], the hull construction environmental impacts are based on the welding processes performed during the construction. Based on projections from research performed earlier, a carbon intensity can be attributed to based on the cutting, bending and welding performed to construct the hull. The steel used in ship construction is primarily processed through welding and cutting. Research conducted by Gilbert estimates that the carbon intensity for welding and cutting is approximately 1.7324 tonnes of CO_2 per tonne of hull steel of a container vessel. Bending is not mentioned as having a significant emission impact. The welding process utilizes Gas Metal Arc Welding (GMAW) with specific materials (e.g., E70S wire), and emissions are tied to both the electrode used and the CO_2 emissions from the process.

6.1.3. Sandblasting During Ship Construction

During the construction of the ship, sandblasting is used to clean and prepare the hull surfaces. The process requires 0.023 kg of diesel per square meter of hull surface. Based on the estimated hull surface areas and using a conversion factor of 2.15 kg CO_2 per kg of diesel, the total CO_2 emissions resulting from sandblasting during construction can be calculated and expressed per square meter of hull surface.

6.1.4. Painting and Coating Emissions

From the literature, there is a lack of specific carbon intensity data for the painting process in ship construction. For this study, carbon intensity data has been sourced from Ulstein Norway's initial estimates, providing the following values for the carbon intensity of both interior and exterior painting:

- **Interior Painting**: (...) tonnes CO_2 per square meter
- **Exterior Painting**: (...) tonnes CO_2 per square meter

The total painted surface area of the ship is divided into interior and exterior sections. Using Ulstein's approach, the interior surface area is estimated.

(...)

The exterior surface area is assumed to be approximately half the size of the interior area, based on initial estimates:

$$\text{Exterior Area} = 0.5 \times \text{Interior Area}$$

Using these estimated areas, the total emissions from painting are calculated as:

$$\text{Total Painting Emissions} = (\text{Interior Area} \times (...)) + (\text{Exterior Area} \times (...))$$

This methodology ensures that the emissions from painting are incorporated into the lifecycle assessment, even in the absence of precise emissions data from other sources.

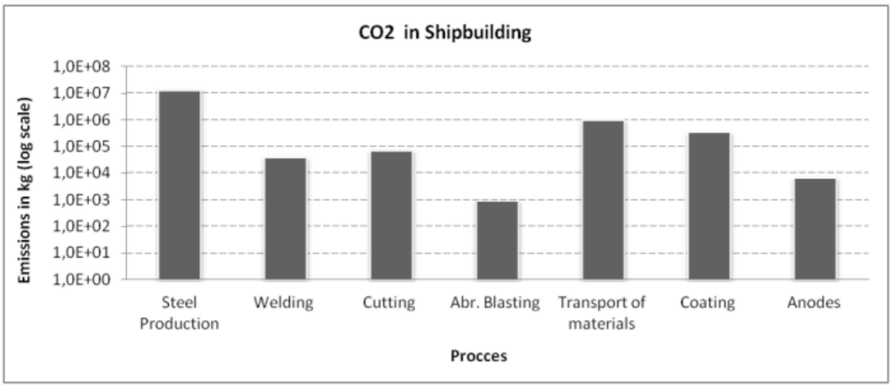


Figure 6.2: Carbon Dioxide emissions per shipbuilding process of the Panamax tanker, studied by Chatzinikolaou et al. 2016

The coating process in shipbuilding is also a significant contributor to the overall CO_2 emissions. Chatzinikolaou et al. [45] (also shown in figure 6.2) provide an estimate of approximately 1,000 tonnes of CO_2 for the coating process on a Panamax tanker with a deadweight tonnage (DWT) of 75,000 tonnes. When distributed across the total surface area of the vessel, this results in a carbon intensity of 0.027 tonnes CO_2 per square meter (or 27 kg CO_2/m^2).

In comparison, the estimate provided by Ulstein Norway for a similar vessel's coating process gives higher values of carbon intensity, with (...) tonnes CO_2/m^2 for interior painting and (...) tonnes CO_2/m^2 for exterior painting. These values would result in higher total emissions when applied to a Panamax tanker.

For instance, using the Norwegian estimate on the same Panamax tanker, the total CO_2 emissions for the coating process would be (...) Chatzinikolaou et al. estimate. This discrepancy highlights the variability in emission estimates depending on the methodology and assumptions regarding surface areas and carbon intensities.

It is important to note that the current study focuses on a heavy transport vessel designed for monopile transportation, which may align more closely with vessels typically constructed by companies like Ulstein. These vessels are often subject to different operational and construction parameters compared to Panamax tankers. As such, using the higher carbon intensity values from Ulstein's estimates may provide a more accurate representation of the environmental impact of painting and coating for these specialized vessels. The higher emissions predicted by the Norwegian estimate suggest that greater attention to coating processes may be required, particularly in efforts to reduce the overall environmental footprint of large vessels such as the heavy transport vessels used for monopile transport.

6.1.5. Machinery Production Data

In the context of assessing the carbon intensity of general ship machinery production, specific values for marine machinery are scarce in the available literature. However, the Ulstein Norway estimate provides a conservative and practical benchmark for machinery production, suggesting a carbon intensity of (...) tonnes CO_2/tonne for ship machinery. This estimate reflects the greater material complexity and energy intensity involved in producing large marine machinery, which includes auxiliary systems, control units, and other mechanical components essential to a ship's operation.

Attribution Based on Steel Content: Given that a significant portion of ship machinery is constructed from steel, one method for estimating carbon emissions is to apply the known carbon intensity of steel production, which typically ranges from 1.8 to 2.5 tonnes CO_2/tonne of steel. However, this simplified method does not account for the full complexity of marine machinery, which includes diverse materials and intricate systems that extend beyond steel. The higher estimate from Ulstein better captures the more realistic emissions associated with producing machinery for heavy-duty marine applications.

Thus, while the steel-based approach offers a useful lower bound for machinery production emissions, the Ulstein estimate of (...) tonnes CO_2/tonne serves as a more cautious and likely more accurate figure. This estimate is used in further calculations, and the impacts on design decisions resulting from the uncertainty of the data used will be addressed in chapter 9.

6.1.6. Engine Production

Engines represent one of the most complex components of a ship, based on *Blended*'s estimates for resistance and propulsion an estimate for engine weight is calculated [34]. A carbon intensity can be attributed to the production of this engine. For marine engines, an estimate of carbon intensity can be derived from comparisons with related industries. Although no direct data is available for marine engines, insights from the automotive industry offer a useful reference point.

In the automotive sector, the drivetrain of a standard mid-sized gasoline internal combustion engine (ICE) vehicle has been calculated to have a carbon intensity of approximately 5 tonnes CO_2/tonne engine, according to Helmers et al. (2020) [103]. This value is based on a drivetrain weight of 0.3148 tonnes and corresponding emissions of 1.574 tonnes CO_2. While automotive drivetrains are not 100% comparable to marine engines, this provides a baseline for understanding the lower end of engine-related carbon emissions.

Ulstein Norway estimates a carbon intensity of (...) tonnes CO_2/tonne machinery for the production of ship machinery, which includes engines. This higher value reflects the greater material use and energy required for producing large diesel engines, their fuel systems, and associated electronic components. The scale and operational demands of marine engines are significantly greater than those of automotive drivetrains, justifying the higher carbon intensity. As the same scope of emissions is considered in both cases, ship-specific systems could contribute to a difference in carbon intensity.

The difference between automotive drivetrain carbon intensity (5 tonnes CO_2/tonne) and Ulstein's estimate ((...) tonnes CO_2/tonne) for marine engines highlights the importance of refining lifecycle assessments to account for industry-specific conditions. The Ulstein estimate provides a more reliable reference for capturing the environmental impact of marine engine production, but further validation with direct data from the shipbuilding industry would be beneficial to ensure accuracy. The impact of these different carbon intensities will be discussed in chapter 9.

6.1.7. Transport of materials

The data used for calculating emissions from steel transportation during shipbuilding is primarily based on two factors: distance traveled (both by land and sea) and the carbon intensity of transportation. The carbon intensity is region-specific and accounts for the varying emissions of different transportation modes.

The distances for land and sea transport are recorded in kilometers (km). This data is region-specific and reflects the transport routes commonly used between steel production sites and shipyards. The carbon intensity is expressed in terms of CO_2 emissions per tonne-kilometer (tkm), with separate values for land and sea transport.

For sea transport, an emission factor of 0.0000119 tonnes CO_2/tkm is applied. This figure is based on data from studies on maritime cargo emissions. For instance, Gilbert (2017) [15] provides data for shipping steel from Shanghai to Okpo-dong, South Korea, with a seafaring distance of approximately 822 km. Using this emission factor, the emissions associated with steel transportation in this scenario amount to 537.46 tonnes of CO_2.

For land transport, an emission factor of 0.0011235 tonnes CO_2/tkm is assumed from literature [15]. This factor is applicable for regions with steel transport by road or rail, and it varies depending on the region and infrastructure. For each region, the share of land versus sea transport is recorded to reflect the proportion of emissions arising from different transportation modes.

6.2. Operation

Based on fuel consumption and carbon intensity of fuel as calculated by Zwaginga et al. (2021)[34] and Peeten (2022) [32], CO2 emissions can be attributed to the emissions of the HTV. No additional data is used for doing this.

6.3. Maintenance

Maintenance is conducted at regular intervals throughout the vessel's lifetime, typically every 2.5 or 5 years [15].These inspections include routine tasks to assess coating degradation, identify structural deficiencies, and evaluate the extent of hull fouling. [104]. With a design lifespan of 30 years for each hull, there are several scheduled maintenance periods before end of life. As mentioned before, this study accounts for welding, cleaning (sandblasting), painting, during maintenance cycles. The following assumptions are made for the lifecycle assessment:

6.3.1. Steel Maintenance and Replacement During Maintenance

Throughout the ship's 30-year operational lifespan, 10% of the vessel's steel is assumed to be replaced due to corrosion and mechanical stress[15]. This replacement is spread across multiple maintenance cycles, ensuring that critical structural components maintain their integrity.

This replacement contributes significantly to CO_2 emissions, as the production and transport of steel are both carbon-intensive processes. Using the steel intensities and regional carbon data, the emissions from steel used in maintenance can be calculated using the formula provided in the emission calculation model:

$$\text{CO}_2\text{ Emissions from Steel} = 0.1 \times (W_{\text{st}} + W_{\text{super}}) \times \text{Adjusted Carbon Intensity}$$

Where W_{st} is the steel weight of the hull and W_{super} is the weight of the superstructure. This accounts for both steel production and transportation.

6.3.2. Welding

During each maintenance interval, 5% of the welds are reinforced. According to data provided by Gilbert et al. (2017) [15], the carbon intensity for welding is calculated based on the amount of steel used and the energy consumed per meter of welding, as well as grid electricity factors for converting energy consumption into CO_2 emissions.

The emission calculation for welding follows this formula:

$$\text{CO}_2\text{ Emissions from Welding} = 0.05 \times W_{\text{st}} \times \text{Carbon Intensity for Welding}$$

With W_{st} being the steel used in the construction phase and the welding carbon intensity accounting for the energy requirements during reinforcement.

6.3.3. Cleaning

The cleaning process during maintenance, particularly sandblasting, also contributes to emissions. The underwater surface area to be cleaned is calculated using the ship's dimensions (length, breadth, and draft). The diesel consumption for sandblasting is assumed to be 0.023 kg diesel per square meter of surface area [15]. Using a conversion factor of 2.15 kg CO_2 per kg diesel, the total emissions from cleaning can be expressed as:

$$\text{CO}_2\text{ Emissions from Cleaning} = \text{Surface Area} \times 0.023 \times 2.15$$

This formula accounts for both the underwater and topside cleaning requirements over the vessel's lifetime. Besides, 50% of the hull is repainted and protected during each maintenance period [15].

6.4. End of Life

The decommissioning and dismantling of ships present unique challenges for lifecycle assessments, as the recycling and disposal processes vary widely across the globe. In practice, most ships are dismantled in South Asia, where processes often lack the technological sophistication of shipbuilding. These sites focus on maximizing material recovery, but the environmental practices are often substandard, leading to higher emissions.

6.4.1. Cutting and Material Processing

At the end of the ship's life, emissions from cutting the steel components are significant. The total surface area to be cut is calculated based on the ship's dimensions (length, breadth, and draft). The energy required for cutting is assumed to be 8.5 MJ per square meter, with a conversion factor of 0.14 kg CO_2/MJ [15]. The formula for emissions from cutting is:

$$\text{CO}_2\text{ Emissions from Cutting} = \text{Total Surface Area} \times 8.5 \times 0.14$$

6.4.2. Transport of Scrapped Materials

Following the cutting phase, the steel recovered from dismantling is transported to recycling facilities. Emissions from this transportation are based on the weight of the steel and the distance it needs to travel by land and sea, specific to the region where the ship is dismantled. The formula for transport emissions is:

$$\begin{aligned}\text{CO}_2\text{ Emissions from Transport} = {} & W_{\text{steel}} \times (\text{Distance by Land} \times \text{Land Transport Factor} \\ & + \text{Distance by Sea} \times \text{Sea Transport Factor})\end{aligned}$$

6.4.3. Recycling Efficiency

Research indicates that recycling efficiency differs depending on the type of ship and the dismantling method employed. For example, re-rolling scrap steel from decommissioned ships into construction materials bypasses the energy-intensive billet and ingot casting stages. Tilwankar et al. (2008)[105] found that this re-rolling process produces significantly fewer emissions—approximately 2.7 times lower—compared to producing virgin steel from iron ore.

For tankers, up to 81% of the steel can be recovered, depending on the condition of the ship. The remainder of the steel (approximately 8–10%) is typically lost due to corrosion [105].

However, the potential negative impacts of reusing steel in other industries, such as potential decreases in material quality or increased energy consumption during processing, have not been taken into account in this lifecycle assessment. These factors are not currently included in the ship design tool, as it is unclear wether these negative impacts can be attributed to the lifecycle emissions of the disposed vessel or to the future application of the use of the vessel. Future iterations of this tool may require adjustments to better reflect the trade-offs and inefficiencies that arise when steel is repurposed in different sectors.

6.5. Conclusion

This chapter has outlined the critical importance of accurate and reliable data collection for performing a robust lifecycle assessment (LCA) for ship design, particularly within the framework of the *Blended* tool. The data collected spans various phases of the ship's lifecycle, from construction and operation to maintenance and end-of-life processes. In line with the chapter 5: Scope it was determined that key focus areas should include steel production and sourcing, machinery production, painting, and maintenance activities, as these factors contribute significantly to the overall lifecycle emissions.

The detailed inventory of emissions, based on both literature and industry data from Ulstein Verft, provides a comprehensive foundation for quantifying the environmental impacts of shipbuilding and operation. By incorporating geographical variations in carbon intensities, particularly for steel sourcing, the chapter highlights the significant differences in emissions based on material origin. Moreover, specific processes such as welding, painting, and sandblasting have been broken down to reflect their respective contributions to lifecycle emissions.

The collected data will now be integrated into the design tool, enhancing its ability to assess the environmental performance of ship designs accurately. By doing so, it supports the optimization of vessel designs in alignment with sustainability targets and emission reduction strategies. The findings presented here will be used to inform the subsequent analysis in the following chapters, where case studies and scenario analyses will demonstrate the effects of these data-driven insights on real-world ship design decisions.

7

Module

This chapter outlines the structure and methodologies used in the module developed for calculating the carbon intensity of a vessel across its entire lifecycle, as determined in **step 4** in the method. The module covers emissions from various phases, including material sourcing, construction, maintenance, and the end-of-life stages of a ship. Each phase is examined to provide a comprehensive estimate of the total CO_2 emissions associated with the vessel's operations and life cycle. Together with the assumptions made in chapter 6, this will answer **subquestion 3** of the research question, being: *How can Blended Design be expanded to include a full life cycle assessment, including cost and GHG emissions in the ship building and decommissioning?*.

The following sections describe the methodology for calculating emissions from material sourcing, construction activities, maintenance operations, and end-of-life procedures, along with an adjusted EEDI that accounts for life cycle emissions.

Besides, in accordance with **step 5: impact modeling** and **step 6: sustainability indices**, the module is programmed to incorporate adjusted carbon intensity metrics, integrating lifecycle emissions from sourcing key materials, fuel consumption, and operational parameters to calculate an enhanced Energy Efficiency Design Index (EEDI). This is done within the boundaries set in the scope (Chapter 5). As outlined in Section 7.7, this new approach ensures that not only operational emissions, but also emissions related to material production and disposal, are captured in a sustainability index, providing a more comprehensive view of a vessel's overall environmental impact. The chapter concludes by addressing the weighting step, which was defined as **step 7** in the methodology.

7.1. General Build-Up of the Module

The Python module is structured to calculate lifecycle emissions for various stages of a ship's lifecycle, as outlined in the research scope in Chapter 5. The module operates by separating the emissions into distinct functions for each lifecycle phase—sourcing, construction, maintenance, operation, and end-of-life. Each function calculates the emissions for a specific activity, such as steel sourcing or transport, before aggregating the emissions to obtain a total impact assessment. This modular approach ensures flexibility, scalability, and ease of integration into the *Blended* tool.

7.1.1. Emission Calculation Functions

The core structure of the module is built around functions that calculate CO_2 emissions for different lifecycle components:

- **Sourcing Functions:** These calculate emissions related to the sourcing of steel, machinery, and other components. For instance, `emission_sourcing_steel()` computes steel emissions, adjusting for regional production methods.
- **Transport Functions:** Functions like `emission_transport_steel()` handle emissions from transporting materials by land and sea, accounting for distances and regional factors.
- **Construction Functions:** These include calculations for processes such as hull assembly, machinery installation, and painting. For example, `emission_construction_steel()` calculates emissions from hull assembly.

- **Maintenance Functions:** Emissions from maintenance activities, including steelworks and hull cleaning, are captured by functions like `emission_maintenance_steel()`.
- **End-of-Life Functions:** Dismantling emissions are calculated by functions such as `emission_cutting_end_of_life()`, which estimates emissions from cutting and transport.

7.1.2. Aggregation of Emissions

The module also includes functions to aggregate emissions from each phase:

- **Total Emission Calculation:** The `calculate_co2_emission_total()` function combines emissions from all lifecycle phases to provide a total CO_2 emission value.
- **Weighted Emission Calculations:** Functions like `calculate_weighted_co2_emission_range()` allow for scenario-based analyses by applying different weights to operational and maintenance phases.

This modular structure ensures that the module aligns with the data requirements and methodologies discussed earlier, while allowing for future expansion and customization.

7.1.3. Typical Structure of a Function

Each function in the module is designed to perform a specific calculation related to the lifecycle CO_2 emissions of the ship. The functions are structured to be flexible, allowing for inputs that correspond to different variables, such as the weight of steel used, transport distances, and carbon intensities. Below is an example of how a typical function is structured within the module.

`emission_sourcing_steel()` is a function that calculates the CO_2 emissions associated with the steel used in ship construction. It takes as inputs the amount of steel, the region of sourcing, and the year of construction to account for variations in carbon intensity. The function looks up relevant data for the region and year, applies the necessary conversion factors, and returns the calculated emissions.

```
def emission_sourcing_steel(steel_used_construction, region, year, carbon_intensity_data_steel):
    """
    Calculate emissions for sourcing of steel used in construction.

    Parameters
    ----------
    steel_used_construction : float
        Amount of steel used in construction phase to construct ship [tonnes].
    region : str
        Region name (e.g., 'Europe', 'America', 'Korea', 'Japan', 'China', 'India').
    year : int
        Year for which the emissions are being calculated.
    carbon_intensity_data_steel : dict
        Dictionary containing carbon intensity data for steel by region and year.

    Returns
    -------
    emission_construction_steel : float
        CO2 emissions from steel used during construction [tonnes CO2].
    """
    # Fetch carbon intensity for the given region and year
    carbonintensity_steel = get_adjusted_carbon_intensity(region, year,
    carbon_intensity_data_steel)

    # Add 10% extra steel for construction losses
    return 1.1 * steel_used_construction * carbonintensity_steel
```

The structure of the function follows a typical pattern:

- The `docstring` provides a description of the function, detailing its purpose, the input parameters, and the expected output.

- The parameters (in this case `steel_used_construction`, `region`, `year` and `carbon_intensity_data_steel`) are passed into the function.
- The function then retrieves the carbon intensity data for the specified region and year, for example by using a helper function `get_adjusted_carbon_intensity()`.
- The final emissions are calculated with the input parameters returning the result.

This example illustrates how emission functions are structured, using inputs to perform specific calculations that contribute to the total lifecycle emissions. Each function in the module follows a similar pattern, allowing for flexibility and scalability when additional factors need to be incorporated. Separate functions combine these calculations to return the emissions for every lifecycle phase.

7.2. Material Sourcing

The material sourcing process for the ship's construction involves the calculation of emissions associated with the sourcing, transportation, and installation of key materials, namely steel, machinery, and engines. The following sections describe the approach used to quantify emissions from these components, ensuring that the overall environmental impact of the sourcing phase is fully captured.

7.2.1. Steel Sourcing Emissions

The steel used in the ship's construction is one of the primary contributors to emissions during the sourcing phase. The methodology for calculating steel-related emissions is based on the amount of steel used and the regional carbon intensity for steel production `steelusedconstruction, region, year, carbonintensitydatasteel`.

Steel Usage and Carbon Intensity

The emissions from steel sourcing were modeled by determining the amount of steel required in the construction phase. To account for regional differences, the carbon intensity of steel production was adjusted based on the specific region (e.g., Europe, America, Korea, Japan, China or India) and the year of construction. This regional adjustment is essential because the carbon intensity of steel production varies significantly based on the energy mix and production technologies in different parts of the world. An additional 10% steel usage was factored into the calculation to account for losses during construction, such as material wastage.

$$\text{Emissions from steel sourcing} = 1.1 \times \text{steel used} \times \text{carbon intensity of steel (region, year)}$$

7.2.2. Steel Transportation Emissions

In addition to the emissions from steel production, the transportation of steel to the shipyard also contributes to the total emissions in the material sourcing phase. The model for steel transportation emissions includes both land and sea transport.

Transport Distance and Emission Factors

The transportation emissions are based on the total weight of the ship's steel and the distances that the steel is transported via land and sea routes. For each region, the relevant distances were obtained from a dataset, which also provides the share of transport by land and sea. These distances are then multiplied by region-specific emission factors for land and sea transport, which reflect the carbon intensity per tonne-kilometer (t/km). The total transportation emissions are the sum of the emissions from both transport modes, weighted by the proportion of steel transported over land and sea.

$$\text{Emissions from land transport} = \text{LWT} \times \text{distance}_{\text{land}} \times \text{emission factor}_{\text{land}} \times \text{share}_{\text{land}}$$

$$\text{Emissions from sea transport} = \text{LWT} \times \text{distance}_{\text{sea}} \times \text{emission factor}_{\text{sea}} \times \text{share}_{\text{sea}}$$

$$\text{Total transport emissions} = \text{Emissions from land transport} + \text{Emissions from sea transport}$$

7.2.3. Machinery Sourcing Emissions

Machinery used during the construction phase of the ship also contributes to emissions, primarily through its production. The model estimates emissions from sourcing and installing the machinery by calculating the total weight of machinery required and applying an appropriate carbon intensity factor.

Machinery Carbon Intensity

The total emissions from machinery sourcing are calculated by multiplying the weight of machinery used in construction by the carbon intensity factor for machinery production. This factor accounts for the energy and material inputs required to manufacture the machinery components installed in the ship.

$$\text{Emissions from machinery sourcing} = \text{machinery used} \times \text{carbon intensity of machinery}$$

7.2.4. Engine Sourcing Emissions

Similar to the machinery, the emissions from the engine's sourcing are calculated based on its weight and the carbon intensity of engine manufacturing.

Engine Construction and Carbon Intensity

The emissions associated with the engine are calculated by using the determined weight of the engine used in the ship's construction and multiplying it by the carbon intensity of engine construction. This factor accounts for the emissions produced during the manufacturing process of the engine, including the energy-intensive processes involved in casting, assembling, and testing engine components.

$$\text{Emissions from engine sourcing} = \text{engine used} \times \text{carbon intensity of engine}$$

7.3. Construction Phase Emissions

In the construction phase, emissions are generated primarily through the construction of the steel hull and the painting of both the interior and exterior of the ship. The following subsections outline the methodology used to calculate these emissions, focusing on the use of steel in the hull and the surface area that requires painting.

7.3.1. Steel Hull Construction Emissions

The emissions from hull construction were determined based on the amount of steel required to build the ship and the carbon intensity of the construction process. The carbon intensity reflects the CO_2 emissions per tonne of steel used in the construction phase, accounting for energy consumption and production processes at the shipyard. In this model, steel usage is assumed to include any potential material losses during construction.

$$\text{Emissions from hull construction} = \text{steel used} \times \text{carbon intensity of steel construction}$$

7.3.2. Painting Emissions

The surface area to be painted is calculated based on the ship's dimensions, and the emissions are derived by applying carbon intensity factors for painting interior and exterior surfaces.

Surface Area Calculation

The total painted area includes both interior and exterior surfaces. The interior painted area is estimated as four times the product of the ship's length (L), breadth (B), and a factor of 0.75, which accounts for multiple decks and bulkheads. The exterior painted area is assumed to be half the size of the interior painted area.

$$\text{Interior Area} = 4 \times L \times B \times 0.75 + 3 \times L_{\text{sup}} \times B \times 0.75$$

$$\text{Exterior Area} = 0.5 \times \text{Interior Area}$$

Carbon Intensity of Painting

The carbon intensity for painting the ship is divided into two parts: the interior and exterior. The emissions from painting are calculated by multiplying the respective surface areas by the carbon intensity factors for interior and exterior painting.

$$\begin{aligned} \text{CO}_2 \text{ Emissions from painting} = &\text{Interior Area} \times \text{carbon intensity of interior painting} \\ &+ \text{Exterior Area} \times \text{carbon intensity of exterior painting} \end{aligned}$$

7.4. Maintenance Phase Emissions

During the maintenance phase of the ship's lifecycle, emissions are generated from various activities, including the replacement of steel, weld reinforcements, and cleaning of the ship's surfaces. The following subsections describe the methodology used to calculate emissions related to these key maintenance activities.

7.4.1. Steel Replacement Emissions

Steel replacement during maintenance is necessary due to wear and tear over the ship's lifetime. The emissions from this process are modeled by estimating the amount of steel replaced and applying regional and temporal carbon intensity factors for steel production and construction.

Steel Usage in Maintenance

It is assumed that 10% of the ship's structural steel (including the superstructure) is replaced during each maintenance cycle, based on industry data and literature (e.g., Gilbert et al., 2017). The total amount of steel used in maintenance is determined by the sum of the ship's structural steel weight (W_{st}) and superstructure weight (W_{super}). The regional carbon intensity factor for steel production is adjusted for the specific year and region.

7.4.2. Weld Reinforcement Emissions

Welding is an important part of ship maintenance, particularly for reinforcing structural welds that degrade over time. The emissions from this activity are calculated based on the amount of steel reinforced through welding and the number of maintenance cycles over the ship's lifetime.

Weld Reinforcement

It is assumed that 5% of the welds are reinforced during each maintenance cycle [15]. The emissions are modeled by multiplying the steel used for welding by the carbon intensity of welding per tonne during the construction phase. The total emissions also depend on the number of maintenance cycles, which is determined by the ship's lifetime and the interval between maintenance activities.

$$\begin{aligned}\text{CO}_2\text{ Emissions from weld reinforcements} =& \text{number of maintenance cycles} \times 0.05 \times \text{tonne welds}\\ &\times \text{carbon intensity of construction}\end{aligned}$$

7.4.3. Cleaning Emissions

The surface area cleaned includes both the underwater area and the topside area of the hull. The underwater area is calculated using the block coefficient (C_B), draft (T_{swll}), breadth (B), and length (L) of the ship. The topside area is estimated using the ship's depth (D), length, and breadth. Diesel consumption for sandblasting is assumed to be 0.023 kg per square meter[15].

$$\text{Underwater Area} = ((2 \times T_{\text{swll}}) + B) \times L \times C_B$$

$$\text{Topside Area} = 2 \times (D - T_{\text{swll}}) \times (L + 0.5 \times B)$$

CO_2 Emissions from Diesel Use

The CO_2 emissions from cleaning are calculated by multiplying the total surface area cleaned by the diesel consumption rate and a conversion factor for diesel to CO_2 emissions, which is 2.15 kg CO_2 per kg of diesel.

$$\text{Emissions from cleaning} = \text{number of maintenance cycles} \times (\text{Underwater Area} + \text{Topside Area}) \times 0.023 \times 2.15$$

7.5. End-of-Life Phase Emissions

The end-of-life phase of a ship's lifecycle involves emissions related to the dismantling, cutting, and transportation of materials, primarily steel, for processing or recycling. The following subsections outline the methodology used to calculate emissions during the ship scrapping and material transportation process.

7.5.1. Cutting Emissions at End of Life

At the end of the ship's lifecycle, the dismantling process involves cutting the ship's hull and components into manageable pieces. This process consumes electricity and generates CO_2 emissions. The emissions from cutting the ship are calculated based on the total surface area to be cut and the electricity consumption per square meter.

Surface Area Calculation

The total surface area to be cut includes both the underwater and topside areas of the hull. The underwater area is calculated using the block coefficient (C_B), draft (T_{swll}), breadth (B), and length (L) of the ship. The topside area is estimated using the ship's depth (D), length, and breadth.

$$\text{Underwater Area} = ((2 \times T_{\text{swll}}) + B) \times L \times C_B$$

$$\text{Topside Area} = 2 \times (D - T_{\text{swll}}) \times (L + 0.5 \times B)$$

$$\text{Total Surface Area} = \text{Underwater Area} + \text{Topside Area}$$

Electricity Consumption and CO_2 Conversion

The electricity required for cutting is assumed to be 8.5 MJ per square meter, and the conversion factor for electricity to CO_2 emissions is 0.14 kg CO_2 per MJ for South Korea (as referenced in Gilbert et al.). The total emissions are then calculated by multiplying the surface area by the electricity consumption rate and conversion factor.

$$\text{Emissions from cutting} = \text{Total Surface Area} \times 8.5 \times 0.14/1000$$

$$\text{(Conversion from kg CO}_2\text{ to tonnes CO}_2\text{)}$$

7.5.2. Transportation Emissions for Processing

After the ship is dismantled, the steel and other materials must be transported to processing or recycling facilities. The emissions from this transportation are calculated based on the weight of the steel, the distance transported by land and sea, and the respective CO_2 intensity factors for land and sea transport.

Transportation Distance and Emission Factors

For each region, the distance data for land and sea transport are obtained from the dataset. These distances are multiplied by the carbon intensity factors for land and sea transport, reflecting the CO_2 emissions per tonne of steel per kilometer. The transportation is divided into shares of land and sea transport, as specified for each region.

$$\text{Emissions from land transport} = \text{steelweight} \times \text{share}_{\text{land}} \times \text{distance}_{\text{land}} \times \text{emissions factor}_{\text{land}}$$

$$\text{Emissions from sea transport} = \text{steelweight} \times \text{share}_{\text{sea}} \times \text{distance}_{\text{sea}} \times \text{emissions factor}_{\text{sea}}$$

Total Transportation Emissions

The total emissions from the transportation of steel to processing facilities are calculated by summing the emissions from land and sea transport.

$$\text{Total transportation emissions} = \text{Emissions from land transport} + \text{Emissions from sea transport}$$

7.5.3. Total CO_2 Emission Calculation

The function `calculate_co2_emission_total` aggregates the emissions from all phases (sourcing, construction, maintenance, and end-of-life) to compute the total CO_2 emissions over the ship's lifecycle. This function also includes an operational phase, where emissions from fuel consumption are modeled based on the ship's fuel type, power output, and mission profile.

$$\begin{aligned}\text{Total CO}_2\text{ Emissions} =& \text{Sourcing Emissions} + \text{Construction Emissions} + \text{Maintenance Emissions} \\ &+ \text{Operational Emissions} + \text{End-of-Life Emissions}\end{aligned}$$

This approach ensures that each phase of the ship's lifecycle is accounted for, with the flexibility to adjust parameters such as steel weights, transportation distances, and carbon intensity data for different regions and years. The structure of the code is modular, allowing for detailed phase-by-phase analysis while maintaining the ability to compute the total emissions for the entire lifecycle of the ship.

7.6. EEDI Module: CO_2 Emissions from Fuel Use and EEDI Calculations

The existing EEDI module has been expanded with additional calculations to estimate CO_2 emissions resulting from fuel consumption during the ship's operational phase, as well as simplified Energy Efficiency Design Index (EEDI) calculations. This section describes these enhancements and the underlying methodology used to calculate emissions based on fuel use and operational efficiency metrics.

7.6.1. Fuel Consumption and CO_2 Emissions

To quantify the CO_2 emissions from fuel consumption during the vessel's operations, a new function `calculate_fuel_consumption` was introduced. This function models fuel consumption based on various operational parameters, such as installed power, vessel speed, and mission-specific data, and uses fuel-specific characteristics to estimate the total fuel consumption for a given mission.

Fuel Consumption Calculation

Fuel consumption is primarily driven by the vessel's power demands, both for propulsion during transit and for dynamic positioning (DP). The calculation takes into account the vessel's speed, the time spent in DP, and the loading/unloading times for each mission. The power demand is adjusted for the load on the installed power system during these activities.

$$\text{Fuel Consumption} = \frac{\text{Number of trips per year} \times \text{Total mission time} \times P_{\text{inst}}}{10^6}$$

$$\times \text{ Engine Load} \times \text{Specific Fuel Consumption}$$

where:

- P_{inst} is the total installed power.
- *Engine Load* accounts for varying load factors during transit, DP operations, and cargo handling.
- *Specific Fuel Consumption* is the fuel consumption per kilowatt-hour, derived from fuel-specific data.

CO_2 Emissions from Fuel Use

The CO_2 emissions from fuel consumption are calculated using the `CO2emissionsfuelmodel` function, which retrieves fuel-specific carbon factors (C_{FME}) from the alternative fuels table. These carbon factors account for CO_2 emissions as well as additional contributions from methane (CH_4) and nitrous oxide (N_2O), expressed in CO_2 equivalents.

$$\text{Annual CO}_2 \text{ Emissions} = \text{Fuel Consumed} \times (C_{\text{FME}} + 25 \times C_{\text{CH4}} + 298 \times C_{\text{N2O}})$$

The total CO_2 emissions over the vessel's lifetime are then computed by multiplying the annual emissions by the ship's lifetime in years:

$$\text{Total CO}_2 \text{ Emissions} = \text{Annual CO}_2 \text{ Emissions} \times \text{Lifetime}$$

7.7. Proposal for Adjusting the EEDI to Incorporate LCA Emissions

In Peeten's research (2022)[32], the EEXI score for HTV vessels was introduced in *Blended*. Building on this method, steps 5 and 6 propose the introduction of sustainability indices that account for lifecycle emissions. To ensure alignment with the EEDI methodology focused on operational emissions, an expression of lifecycle emissions within the EEDI framework is suggested. This approach proved valuable when exploring design phases in Peeten's research. In this section, the extension of the EEDI framework to include non-operational lifecycle emissions will be discussed.

7.7.1. Overview

The Energy Efficiency Design Index (EEDI) is a key regulatory measure to ensure ships meet specific energy efficiency standards. However, current formulations of the EEDI primarily focus on operational fuel consumption and do not account for emissions from the entire life cycle of the fuel and vessel. To address this gap, a proposal for an adjustment of the EEDI formula that integrates emissions from the life cycle assessment (LCA) of the vessel and fuel, referred to as LCA EEDI.

The LCA EEDI score is designed to be more comprehensive by including emissions related to fuel production, transportation, and vessel construction. This approach provides a more accurate representation of the environmental impact of a vessel over its lifetime.

7.7.2. Proposed Calculation Method

The adjusted EEDI score, denoted as *LCA EEDI*, is calculated by adding the LCA emissions component to the traditional EEDI formulation [106]. The calculation considers the vessel's installed power, brake power, fuel type, and specific mission profiles, as well as additional emissions factors like methane (CH_4) and nitrous oxide (N_2O). The adjusted formula for *LCA EEDI* is as follows:

$$\text{LCA EEDI} = a\left(\frac{EEDI_{ME} + EEDI_{AE} + EEDI_{PTI} - EEDI_{mecheff}}{\text{Correction factors}}\right) + b\left(\frac{CO_2^{LCA}}{\text{Capacity} \times \text{Total Distance}}\right)$$

Where:

- $EEDI_{ME}$ is the contribution of the main engine power and fuel consumption to emissions.
- $EEDI_{AE}$ is the contribution from auxiliary engines.
- $EEDI_{PTI}$ accounts for the power take-in contribution.
- $EEDI_{mecheff}$ is the mechanical efficiency correction factor.
- Correction factors includes a range of correction factors, such as ice conditions, cargo type, and ship speed.
- CO_2^{LCA} is the life cycle CO_2 emissions excluding operational emissions.
- Capacity refers to the deadweight tonnage (DWT) or equivalent cargo carrying capacity of the vessel.
- Total Distance represents the total operational distance covered by the vessel over its lifetime.
- a and b are weighting factors applied to balance the influence of operational and life cycle emissions in the final score.

7.7.3. Mission-Specific Considerations and the Need for Weighting Factors

When dealing with shorter mission distances and substantial dynamic positioning (DP) time, the LCA component, particularly construction emissions, can have a disproportionate influence on the LCA EEDI score. This is because the total lifetime emissions related to construction are spread across fewer operational kilometers, leading to a higher per-kilometer impact from construction. Conversely, in missions with longer sailing distances, operational emissions dominate, and the construction contribution becomes relatively smaller, which dilutes the LCA's impact.

To ensure the LCA EEDI score reflects a balanced evaluation of both life cycle and operational emissions, mission-adjusted weighting factors a and b are introduced. These factors allow for fine-tuning the relative contribution of operational and LCA emissions, depending on the specific mission profile. For missions involving shorter distances and higher DP times, increasing a would maintain the focus on operational efficiency, while b could be adjusted to avoid over-penalizing vessels for their construction-related emissions.

The mission-adjusted weighting approach ensures that the LCA EEDI remains a true indicator of the vessel's real-world environmental performance. It prevents scenarios where the construction component disproportionately skews the score for missions where operational emissions are not dominant.

This adjustment is essential for achieving a balanced and comprehensive evaluation, particularly when vessels have a wide range of mission profiles involving varying distances and operational modes.

7.7.4. Benefits of the Mission-Adjusted Weighting Approach

By introducing weighting factors a and b, the proposed LCA EEDI calculation allows for greater flexibility in how life cycle and operational emissions are represented. The weighting factors can be adjusted according to the type of mission, ensuring that:

- For shorter-distance missions with extensive DP time, the influence of construction-related LCA emissions does not disproportionately dominate the final score as result of a higher emission values for lower distances sailed.
- For longer-distance missions, where operational emissions play a larger role, the contribution of LCA emissions is moderated to reflect their reduced relative importance.
- The operational EEDI calculation remains intact, providing consistency with existing methodologies, while the LCA component offers a meaningful expansion of the assessment scope, ensuring a holistic environmental evaluation of the vessel.

This method makes the LCA EEDI not just a simple alternation of the traditional EEDI but a significant expansion that incorporates life cycle emissions without overshadowing operational efficiency. This balance is key for addressing the broader environmental impacts of maritime operations while keeping regulatory and industry priorities aligned.

$CO_2{}^{LCA}$ Term

The term CO_2^{LCA} represents the life cycle CO_2 emissions associated with the fuel and vessel. These emissions encompass not just the direct emissions from fuel combustion during vessel operations but also emissions from upstream and downstream processes such as:

- Extraction and refining of raw materials (e.g., crude oil for fossil fuels or biomass for biofuels).
- Transportation and storage of fuels.
- Manufacturing and disposal of the vessel and its components.

The CO_2^{LCA} term is typically measured in units of mass, such as kilograms of CO_2 equivalent (`kg CO₂eq`), representing the total greenhouse gas emissions expressed in terms of their CO_2 equivalent impact.

Capacity and Total Distance

The denominator of the LCA term in the equation includes the product of the vessel's capacity (in deadweight tonnage, DWT) and the total distance traveled over its lifetime:

$$\text{Capacity} \times \text{Total Distance}$$

- **Capacity:** The vessel's deadweight capacity, typically measured in metric tons (tonnes), represents the total weight of cargo or passengers the vessel can carry.
- **Total Distance:** The total operational distance that the vessel will travel over its lifetime is measured in nautical miles (NM). This term is calculated as the product of the number of trips per year and the lifetime of the vessel, ensuring that the emissions are distributed over the total operational scope of the vessel.

By dividing the total life cycle emissions CO_2^{LCA} by the product of the vessel's capacity and total distance, we effectively normalize the emissions per tonne-mile, which aligns with how traditional EEDI scores are expressed.

Unit Consistency and Alignment

The resulting term, $\frac{CO_2^{LCA}}{\text{capacity} \times \text{total distance}}$, provides a measure of the life cycle emissions per tonne-mile (or tonne-nautical mile) transported, as follows:

$$\frac{\texttt{kg CO}_2\texttt{eq}}{\texttt{tonne} \times \texttt{NM}} = \frac{\texttt{kg CO}_2\texttt{eq}}{\texttt{tonne-mile}}$$

This unit aligns with the structure of the traditional EEDI, which expresses emissions in grams of CO_2 per tonne-nautical mile ($\texttt{g CO}_2\texttt{/tonne-NM}$). However, since the term includes life cycle emissions rather than just operational emissions, it provides a more comprehensive measure of the vessel's environmental impact.

Weighting Factor b

The coefficient b is a weighting factor that adjusts the influence of the LCA emissions on the overall LCA EEDI score. Its value can be determined based on regulatory priorities or desired weighting between operational and life cycle emissions. For example, if life cycle emissions are considered equally important as operational emissions, b could be set such that both terms have comparable contributions to the total LCA EEDI score. Alternatively, b can be adjusted to emphasize or de-emphasize LCA emissions depending on the specific regulatory focus.

Final Interpretation

By incorporating the term $b \times \left(\frac{CO_2^{LCA}}{\text{capacity} \times \text{total distance}}\right)$, the adjusted LCA EEDI score evaluates not only the vessel's operational efficiency but also its environmental performance over its entire life cycle. This ensures that vessels using fuels with higher upstream emissions or those with inefficient production processes are scored appropriately. Furthermore, it incentivizes the use of alternative fuels with lower LCA emissions and encourages ship designs that minimize environmental impact over the vessel's full lifespan.

7.8. Missions for Investigation

To evaluate the environmental and financial performance of different ship designs, three benchmark missions have been selected for analysis. The first two of those missions taken over from the work of Peeten et al. [32]. Besides, an additional mission is formulated. These missions provide a basis for comparing various alternative solutions. The three missions are outlined as follows:

Europe - USA East Coast

The first mission covers the route between Europe and the USA. Specifically, the voyage is set between the port of Rotterdam and the port of New York, spanning a distance of 3,308 nautical miles. At a sailing speed of 13 knots, this journey takes approximately 10 days and 14 hours. This route serves as a typical transatlantic mission, representing the transportation of offshore wind farm (OWF) parts or other cargo between Europe and the east coast of the USA.

Europe - China

The second mission focuses on delivering OWF components from Europe to mainland China, with a voyage set between the port of Rotterdam and the port of Shanghai. This longer route covers a distance of 10,548 nautical miles and takes approximately 33 days and 19 hours to complete. The journey includes passage through the Suez Canal, which incurs additional canal fees. This mission represents a significant long-haul route in the global supply chain for offshore wind installations.

Feeder Mission for Empire Wind

In addition to the benchmark missions, a third mission has been added to analyze the ship's performance in a feeder vessel role. This mission involves the transportation of OWF components to the Empire Wind project, located 40 miles off the coast of Long Island. In this scenario, the vessel would serve as a feeder to a larger construction vessel, such as the Heerema construction vessel. The possibility of using a specialized feeder vessel for this mission is supported by the ongoing construction of a Jones Act-compliant vessel in the US, based on another Ulstein design, highlighting the potential feasibility of this mission.

These three missions offer a diverse range of voyage profiles, from transatlantic to long-haul and feeder operations, enabling a comprehensive assessment of the ship designs' performance across different operational contexts.

7.9. Weighting

In **step 7** of the proposed lifecycle assessment method (in chapter 4), a weighting system is applied to each phase of the ship's lifecycle, allowing for flexible adjustments of the contribution of different phases to the overall CO_2 emissions. This approach ensures that the effect of various components of the lifecycle can be scaled based on their significance, uncertainty, or other project-specific factors.

The key phases where weights can be applied include:

- **Sourcing**: Emissions related to the sourcing of materials, such as steel and machinery, can be weighted to account for differences in material types, transportation distances, or production methods.
- **Construction**: The construction phase involves processes like welding, painting, and assembly. Weights can be applied to each of these activities to reflect variations in energy use or emissions intensities across different construction practices.
- **Maintenance**: Maintenance activities, such as steel replacement, weld reinforcement, and cleaning, occur periodically throughout the vessel's lifetime. By applying weights to these activities, the model allows for adjustments based on the frequency of maintenance or the environmental impact of specific maintenance tasks.
- **Operation**: The operation phase typically generates emissions from fuel consumption. In the model, a weight can be applied to operational emissions to scale their relative importance based on factors like operational efficiency or the vessel's fuel type.
- **End-of-Life**: The dismantling and recycling of the vessel at the end of its life can also be weighted to account for regional differences in recycling practices, transportation of materials, or the efficiency of cutting and processing activities.

Each of these phases can have its own weight, allowing users to emphasize or de-emphasize certain stages of the lifecycle depending on the goals of the assessment. This flexible weighting system can also be used to perform sensitivity analyses, where different scenarios are tested by altering the weights and observing the impact on the total CO_2 emissions.

By applying weights in this manner, the lifecycle assessment provides a more nuanced understanding of emissions distribution across the various phases of the vessel's lifecycle. The total CO_2 emissions are calculated as the sum of the weighted emissions from each phase, ensuring that all stages of the lifecycle are accurately represented based on their environmental impact and relevance to the specific project.

7.10. Conclusion

This chapter presented the development and structure of the module designed to calculate the carbon intensity of a vessel across its entire lifecycle. By incorporating emissions from material sourcing, construction, maintenance, and end-of-life phases, the module provides a comprehensive analysis of the vessel's total environmental impact. Through a modular approach, the tool enables flexibility and scalability, allowing for detailed phase-by-phase calculations while ensuring integration with the overall lifecycle assessment framework.

The introduction of various emission calculation functions—ranging from steel sourcing to fuel consumption—ensures that all significant contributors to lifecycle emissions are captured. Additionally, the module's capacity to adjust carbon intensity metrics and integrate regional data further enhances the accuracy of the assessment. The aggregation of emissions across different lifecycle stages offers a holistic view of the vessel's environmental footprint, going beyond operational emissions to include material production, transportation, and dismantling.

In conclusion, this module enables the expansion of *Blended* to include a full LCA, addressing sub-question 3: *('How can Blended Design be expanded to include a full life cycle assessment, including cost and GHG emissions in the ship building and decommissioning?')* of the research.

8

Results

In this chapter, **Step 8** of the proposed method, 'Comparison with Requirements,' which incorporates multi-criteria decision making, will be further discussed. The capabilities of *Blended* for selecting an optimal vessel design will be covered, followed by a focus on the implications of including lifecycle emissions in *Blended*. General emission insights from the new module will be presented, with emphasis on their effect on EEDI optima and the impact on design decisions. Several case studies will further investigate the importance of accounting for all lifecycle emissions in different scenarios.

Ultimately, this will lead to the answering of research questions 4, 5 and 6, being: *4: How would a full life cycle optimization in Blended Design perform and lead to different choices in early stage vessel design?*, *5. What is the impact of ship building and decommissioning on GHG-emissions based life cycle assessment outcomes?* & *6. What is the impact of ship building and decommissioning on cost based life cycle assessment outcomes?*

8.1. Capabilities of Blended without LCA Addition

Blended, in its core configuration without the LCA tool, is a powerful decision-making platform designed to assess the influence of various design parameters on a ship's operational and economic performance. Its primary focus is on optimizing the return on investment (ROI) by exploring millions of potential designs, ultimately identifying the best-performing design for each specific set of parameters.

8.1.1. Design Parameter Optimization and Pareto Fronts

Blended's core functionality lies in its ability to explore a vast design space, analyzing how different design parameters such as length (L), beam (B), depth (D), speed (V_s), and others influence the ship's ROI. By doing so, it generates Pareto fronts that visually highlight the trade-offs between different design objectives, such as operational efficiency, cost, and profitability.

For example, by evaluating millions of design variations, *Blended* can create Pareto fronts for each individual parameter. These fronts showcase the best-performing designs in terms of ROI, allowing the user to easily identify the "champion" designs for different parameter ranges. This means the tool doesn't just analyze each design in isolation but also considers the relative performance of all possible designs, efficiently narrowing down the optimal choices.

Operational Performance with the EEDI Module

For each design parameter, *Blended* is capable of generating Pareto fronts that show the best operational performance relative to the ROI. These Pareto fronts help identify designs that optimize fuel consumption, reduce emissions, and increase profitability, all while maintaining operational compliance. For example:

- For *speed* (V_s), the tool identifies the most fuel-efficient speeds that also maximize ROI.
- For *depth* (D), it shows how increasing or decreasing depth affects both the vessel's capacity and its fuel consumption.
- For *length* (L) and *beam* (B), the tool determines the optimal dimensions that balance structural efficiency, stability, and economic performance.

8.1.2. Demonstration of identifying the "Champion" Design

Blended's ability to evaluate millions of potential designs means it can efficiently identify the best-performing or ”champion” design for each combination of design parameters. The ”champion” design is the one that maximizes ROI while maintaining compliance with operational and regulatory requirements. *Blended* provides the user with detailed information on how the champion design performs across all relevant metrics, including fuel consumption, operational efficiency, and economic returns.

By focusing on ROI as the key metric, *Blended* enables users to see which design parameters provide the best return while also complying with energy efficiency regulations through the EEXI module. In summary, *Blended*'s core tool without the LCA addition allows for:

- Analysis of millions of design combinations to identify optimal designs for different parameters.
- Generation of Pareto fronts that show the best-performing designs based on ROI and operational efficiency.
- Identification of the ”champion” design that balances compliance, operational efficiency, and profitability.

Blended's core capabilities offer valuable insights for ship designers and operators, enabling them to make informed decisions based on comprehensive analysis of the entire design space. The result is a tool that provides unparalleled optimization of vessel design, allowing users to maximize ROI while maintaining compliance with energy efficiency standards.

With the results from *Blended*, insightful plots can be generated to visualize the ROI and EEDI performance of a vessel over a chosen range of design parameters within the design space. In *Blended*, various parameters are varied systematically, and all possible combinations are considered as potential ship designs. Due to certain constraints, only viable ship configurations are output, as outlined in the research by Zwaginga et al. [34]. For each input parameter, a range of feasible designs is produced, with corresponding performance metrics like ROI and EEDI.

In figure 8.1, individual designs for each parameter are represented as dots. However, in the subsequent plots shown in this report, only the Pareto front will be displayed, highlighting the optimal designs for each parameter. This approach ensures a clear focus on the best-performing configurations across various design criteria. It is important to note that across different plots, these optimal lines may coincide. For example, the design with the best ROI, along with its corresponding length, breadth, depth, and design speed, can be identified consistently across multiple plots, providing a holistic view of the vessel's optimal design choices.

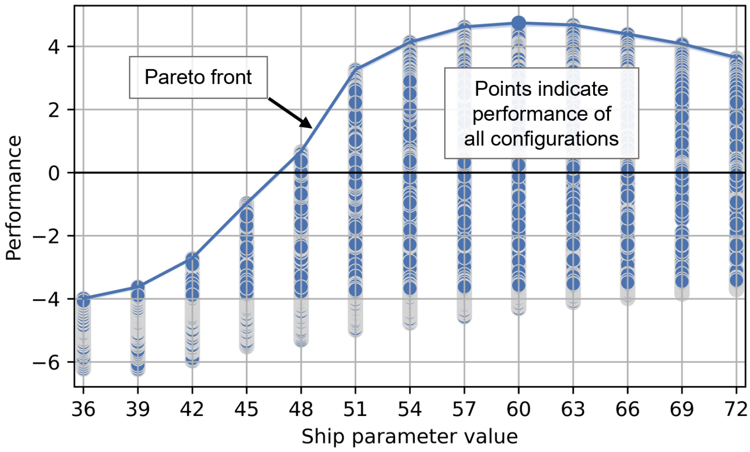


Figure 8.1: Explanation of the plotted figures, from de Ridder et al. (2023)[57]

8.2. HTV Mission Results: A Blended Approach

The results presented here demonstrate the application of a *Blended* EEDI and ROI analysis for the HTV missions. The figures provide insight into the performance of different vessel designs based on parameters such as Length-to-Breadth Ratio (L/B), Foundation Year (number of monopile foundations transported per year), Block Coefficient, Depth, Breadth, and Sailing Speed (V_s). By analyzing these factors, a champion design can be selected that balances operational efficiency and return on investment (ROI).

8.2.1. Initial Design Space for Blended Analysis

These plots provide a glimpse into the design space for the heavy transport Rotterdam- Beijing mission, which was used as the starting point for the *Blended* analysis. The analysis explored different configurations to identify an optimal balance between ROI and EEDI performance. The following design space was utilized:

- **Length (L)**: 200 to 230 meters, in increments of 2 meters.
- **Beam (B)**: 30 to 55 meters, in increments of 2 meters.
- **Depth (D)**: 10 to 17 meters, in increments of 0.5 meters.
- **Speed (V_s)**: 12 to 19 knots, in increments of 0.5 knots.
- **Mission**: HTV on route Rotterdam - Beijing.
- **DP Capability**: 70% of full DNV spectrum.
- **Block Coefficient (CB)**: 0.45 to 0.90, in increments of 0.05.
- **Fuel Type**: HFO (Heavy Fuel Oil).

8.2.2. ROI and EEDI vs Sailing Speed (V_s)

In Figure 8.2a, we observe that as the sailing speed increases, both ROI and EEDI peak around a speed of 16 knots. This suggests that 16 knots is the optimal speed for the mission in terms of both economic performance (max ROI) and environmental performance (min EEDI). Lower and higher speeds result in reduced ROI and increased emissions.

8.2.3. ROI and EEDI vs Breadth

In Figure 8.2b, we see that ROI improves steadily with increasing breadth, peaking around 40 meters. The EEDI follows a similar trend, though the improvement tapers off for breadths above 40 meters. Thus, a vessel breadth of around 40 meters appears to be a good choice.

8.2.4. ROI and EEDI vs Depth

Figure 8.2c shows how vessel depth affects performance. The ROI peaks at a depth of 14 meters, after which both the ROI and EEDI start to decline. This suggests that a depth of around 14 meters provides an optimal balance for the mission.

8.2.5. ROI and EEDI vs Block Coefficient

Figure 8.2d shows similar trends for both EEDI and CB, with an optimal point around CB = 0.75. For higher CB values, corresponding to more cargo transported, the EEDI decreases further.

8.2.6. ROI and EEDI vs Length-to-Breadth Ratio

In Figure 8.2e, we observe that as the Length-to-Breadth ratio increases, the EEDI score tends to decrease, indicating that a higher L/B ratio may reduce emissions per ton-mile. However, the ROI reaches a maximum around an L/B ratio of 5.0 and then decreases. Based on this trend, an optimal L/B ratio would likely fall around this region, offering a good balance between economic and environmental performance.

8.2.7. ROI and EEDI vs Foundation Year

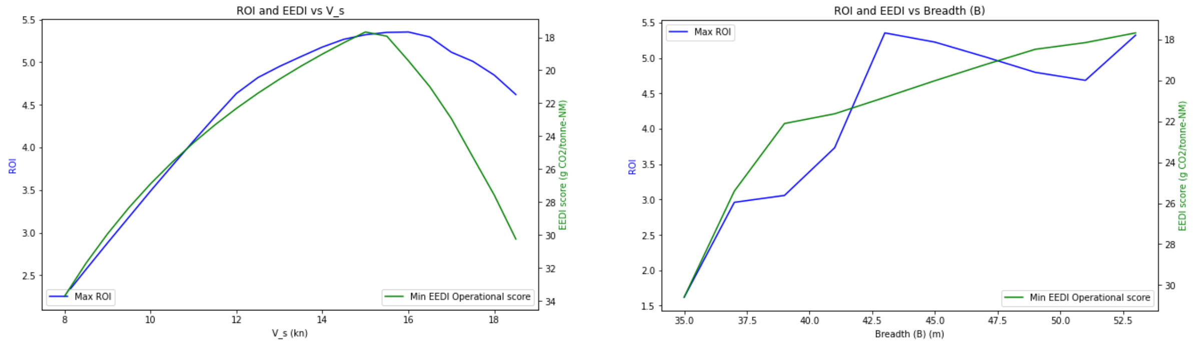
Figure 8.2f illustrates how the number of monopile foundations transported per year (Foundation Year) affects ROI and EEDI. A higher number of monopile transports improves the vessel's ROI and reduces the EEDI. The figure shows a clear Pareto front for both EEDI and ROI, with an optimum ROI at around 2,500 monopiles per year. The EEDI value remains similar across a wide range of monopile transport levels.

8.2.8. Proposed Ship Design Based on the Results

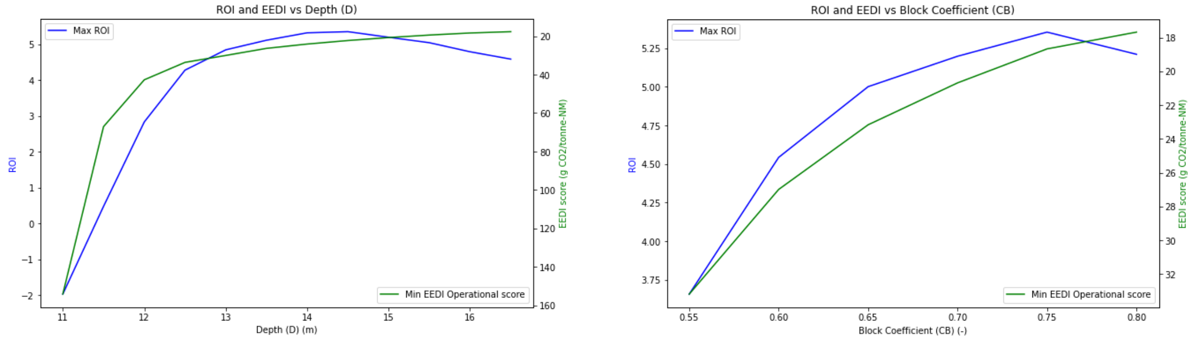
Based on the trends observed in the plots, an optimal vessel design for the HTV mission could have the following characteristics:

- **Length-to-Breadth Ratio**: Around 4.75 to balance good ROI and a low EEDI score.
- **Breadth**: Approximately 43 meters, as the ROI peaks at this breadth.
- **Depth**: Around 14 meters to achieve the highest ROI while maintaining a low EEDI.
- **Block Coefficient**: Around 0.75, where the ROI is highest and EEDI is minimized.
- **Sailing Speed**: 16 knots to optimize both economic performance and emissions reduction.
- **Number of Monopiles**: Around 2500 per year for optimal ROI, while keeping a low EEDI.

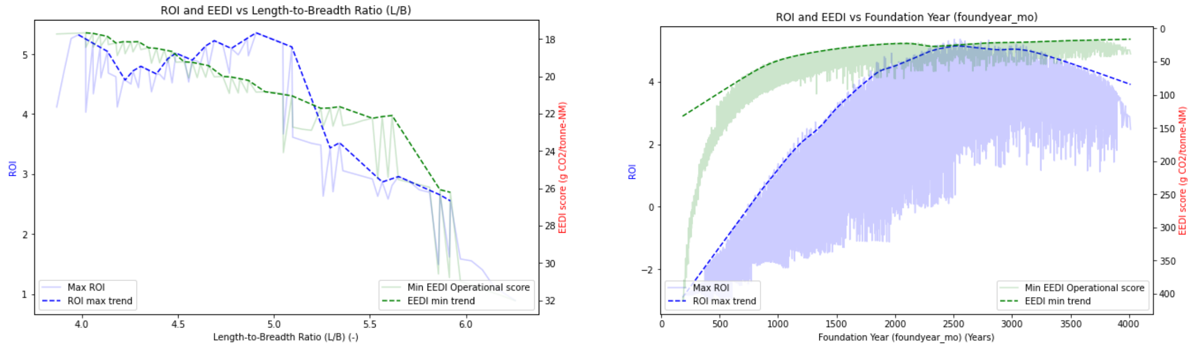
Further analysis would be required to narrow down the final design and fully eliminate utopian points on the pareto fronts. However, these results show how blending ROI and EEDI analyses can help inform the ship design process, ensuring that both economic and environmental factors are considered. As the main aim of this thesis is to investigate to answer the earlier formed research questions, the readers is directed to the research performed by Zwaginga [34], Peeten [32] for further insights in how *Blended* performs.



(a) ROI and EEDI vs Sailing Speed (V_s) **(b)** ROI and EEDI vs Breadth (B)



(c) ROI and EEDI vs Depth (D) **(d)** ROI and EEDI vs Block Coefficient (CB)



(e) ROI and EEDI vs Length-to-Breadth Ratio (L/B) **(f)** ROI and EEDI vs ROI

Figure 8.2: Analysis of ROI and EEDI performance based on different design factors

8.3. Empire Wind

A new mission has been added to Blended, investigating the role of the HTV as a feeder vessel for the offshore wind development project, Empire Wind, as described in Chapter 7.8. The demonstration mission chosen for this study involves the vessel operating as an HTV on the Rotterdam-Beijing route. This route eliminates the influence and uncertainty of weighting factors associated with EEDI calculation, as described in Chapter 7, by excluding DP time. This approach aligns with the methodology of other case studies performed in this study, as well as in earlier research by Zwaginga[34] and Peeten[32].

While the choice of mission does not influence the answering of the research questions in this report, it does affect the optimal ship design. For example, significant differences in optimal design points within the design space would be observed for other missions. In this case, Blended demonstrates that the optimal ROI for the Empire Wind mission is achieved at lower vessel speeds, specifically between 12 and 13 knots, as can be seen in figure 8.3.

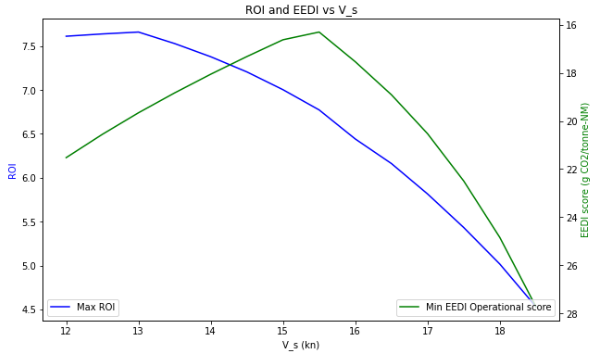


Figure 8.3: EEDI and ROI vs vessel speed for the Empire Wind mission, showing the lower speed at which ROI is optimal

8.4. LCA Addition

The tool provides comprehensive insights into both the *percentage distribution* and *absolute values* of CO2 emissions across various phases of the lifecycle of a heavy transport vessel. It is important to note that the bar chart and pie chart in this analysis represent the emissions profile of a single ship, based on fixed design parameters. These plots serve as an example of the insights that can be gained from the LCA analysis. For any changing parameter (such as length, depth, or fuel type), these results will differ significantly. Therefore, no final conclusions about general design trends can be drawn from these specific examples.

8.4.1. Percentage Distribution of CO2 Emissions by Category and Subcategory

As shown in the pie chart (Figure 8.4), the **operation phase** clearly dominates the lifecycle CO2 emissions, contributing approximately **80%** to **90%** (based on the design parameters) of the total emissions. This highlights that operational efficiency has the greatest potential for reducing the overall emissions footprint of the vessel.

The next most significant contributor is **steel sourcing**, which accounts for **7.7%** of total emissions. This is due to the carbon-intensive nature of raw material extraction and steel production.

Other notable contributors include:

- **Machinery Production:** 2.2%
- **Engine Production:** 2.8%
- **Material Transportation:** 0.2%
- **Painting:** 0.6%
- **Steelworks Maintenance:** 0.2%
- **Weld Reinforcements:** 0.2%

It should be emphasized that this distribution is specific to a specific ship design and operational parameters. For other vessel designs or operational scenarios, the percentage contributions of each category will likely change. The purpose of this example is to demonstrate the potential insights gained through LCA integration, rather than to provide definitive conclusions about the CO2 emission distribution for all heavy transport vessels.

These smaller contributions suggest that while auxiliary activities such as maintenance and minor construction elements play a role, their impact is much less significant compared to the operation phase and material sourcing.

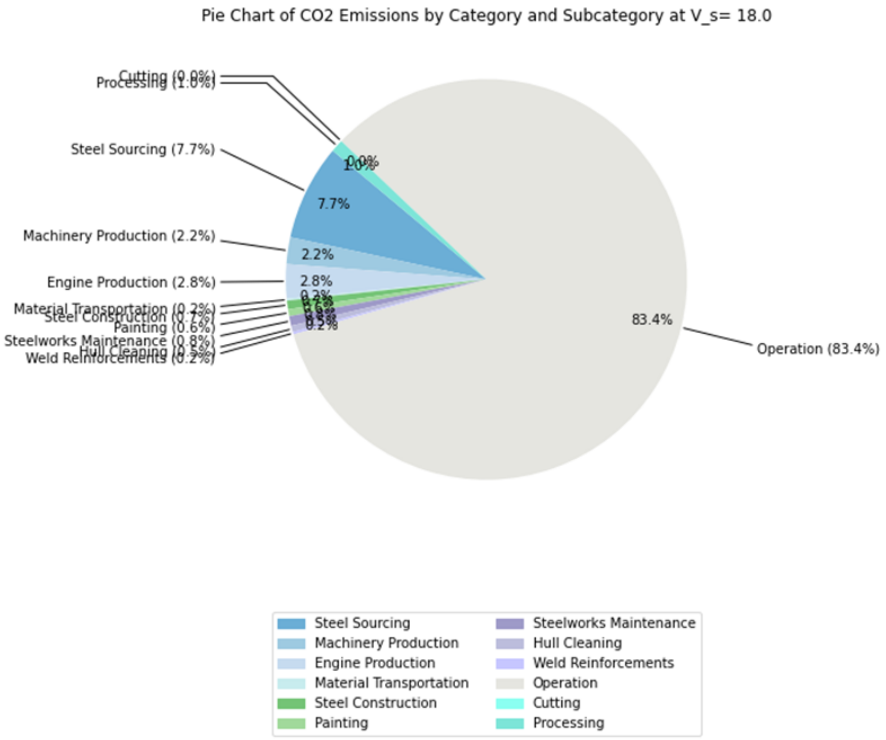


Figure 8.4: Insights into the Lifecycle emissions share from the new tool

8.4.2. Absolute CO2 Emissions per Phase

The bar chart (Figure 8.5) provides a view of the absolute CO2 emissions in tonnes for each phase of the vessel's lifecycle. The data supports the earlier hypothesis that the **operation phase** is the most emissions-intensive, with over **300,000 tonnes** of CO2 emitted during this phase alone. The dominance of this phase further reinforces the need to focus mitigation efforts on optimizing the vessel's operation, such as fuel efficiency and alternative fuel sources.

The second-largest contributor is the **material sourcing phase**, driven largely by steel sourcing, contributing between **50,000** and **60,000 tonnes** of CO2. While smaller in magnitude, it presents a notable area where improvements in raw material production, such as using recycled or low-carbon steel, could reduce lifecycle emissions.

The phases of **construction**, **maintenance**, and **end of life** all contribute significantly less to total emissions. These phases, as shown in Figure 8.5, demonstrate the following characteristics:

- **Construction Phase:** Relatively low emissions, with key contributors being steel construction and painting.
- **Maintenance Phase:** Similarly low, where activities such as *steelworks maintenance* and *hull cleaning* contribute small amounts. These emissions, though lower, could be optimized through less frequent or more sustainable maintenance processes.
- **End of Life Phase:** Minimal emissions, suggesting that the dismantling and disposal of the vessel have limited environmental impact compared to other phases.

8.4.3. Key Takeaways

The insights from both the pie chart and bar chart highlight the following key takeaways:

- The **operational phase** represents the largest source of lifecycle emissions, both in terms of percentage and absolute values. Therefore, optimizing operational efficiency through cleaner fuels, lower speeds, and technological improvements will have the largest impact on reducing total emissions.

- **Material sourcing**, particularly steel production, is the second-largest contributor. Thus, there is potential for significant emissions reductions by sourcing greener materials or improving the efficiency of the production processes involved.
- The phases of **construction**, **maintenance**, and **end of life** contribute relatively small amounts to overall emissions. Incremental improvements in these phases, such as more efficient construction methods or sustainable maintenance practices, can still make a valuable contribution to overall emission reductions.

These findings underscore that while operational improvements are the primary area of focus, secondary phases like material sourcing and maintenance offer additional opportunities for emission mitigation. In the following sections, the impact on design decisions when designing for the lowest lifetime emissions will be further investigated.

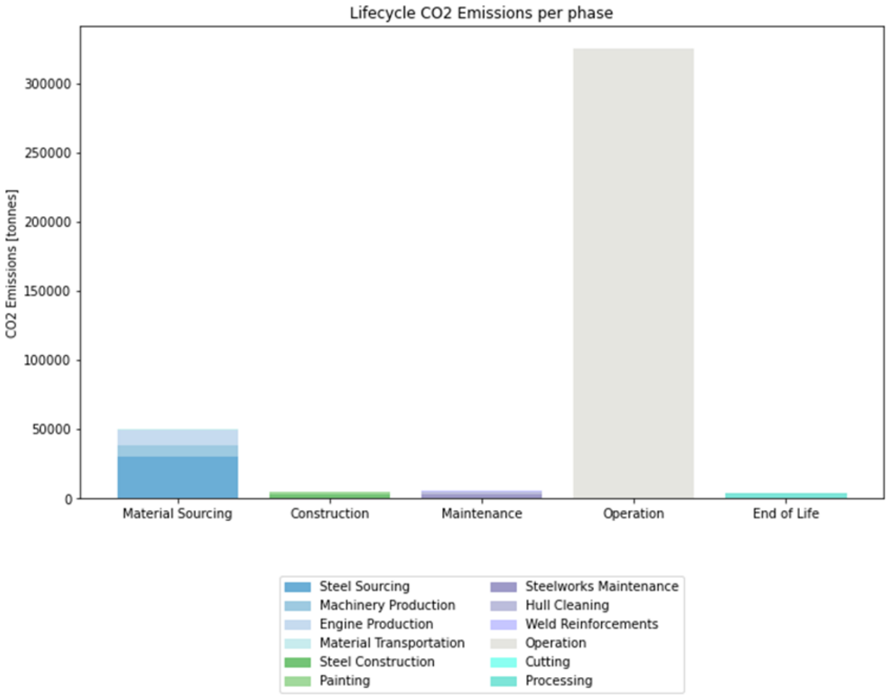


Figure 8.5: Insights into the absolute Lifecycle emissions from the new tool

8.5. Design Implications and Results for the HFO Case

Based on the earlier proposed adjustment of the EEDI score, insight can be given in the influence of the emissions additionally take ino account on the optimal(minimum) EEDI performance for every parameter. The missions chosen to analyze is the vessel being used as HTV on the route Rotterdam - Beijing, as the lack of DP time in this specific mission eliminates the influence and uncertainty of the weighting factors associated with the EEDI calculation, as described in chapter 7. This ensures the full focus of the analysis can be directed to design implications of the incorporation of LCA in chap*Blended*.

8.5.1. Input Parameters and Mission Setup

The input parameters for this analysis include a range of ship design characteristics as well as mission-specific parameters for mission 9. The parameters and their ranges of are as follows:

- **Length (L)**: 200 to 230 meters, in increments of 2 meters.
- **Beam (B)**: 30 to 55 meters, in increments of 2 meters.
- **Depth (D)**: 10 to 17 meters, in increments of 0.5 meters.
- **Speed (V_s)**: 13 to 19 knots, in increments of 0.5 knots.

- **Mission**: HTV on route Rotterdam - Beijing.
- **DP Capability**: 70% of full DNV spectrum.
- **Block Coefficient (CB)**: 0.45 to 0.90, in increments of 0.05.
- **Fuel Type**: HFO (Heavy Fuel Oil).
- **Lifetime**: 30 years.
- **Origin of steel**: China.
- **Maintenance interval**: 5 years.

8.5.2. EEDI Adjustment and Design Insights

The design implications of adjusting the Energy Efficiency Design Index (EEDI) score to account for lifecycle emissions were explored by analyzing the minimal EEDI values for various ship parameters. Specifically, the analysis focused on the *EEDI operational*, *EEDI construction*, and the total *EEDI* scores. The impact of construction emissions, while non-negligible, is relatively small in the case of HFO usage due to the dominance of operational emissions, as shown in Figures 8.6, 8.7, 8.8, and 8.9.

The green lines in the figures represent the **EEDI operational score**, the red lines show the **total EEDI score** (which includes both operational and construction emissions), and the purple lines represent the **EEDI construction score**. Vertical dashed lines indicate the points at which the EEDI scores reach their minimum values for each parameter.

8.5.3. General Trends and Parameter-Specific Optima

Speed (V_s)

In Figure 8.6, the influence of vessel speed on EEDI and ROI is examined. The minimum total EEDI occurs at a speed of around 15.0 knots, as indicated by the red dashed line. The minimal construction EEDI, indicated by the dashed purple line, reaches its minimum at a slightly higher speed of 16.5 knots. Despite the differences in optimal points for construction and operation, the overall minimal EEDI is primarily driven by operational emissions, as construction contributes minimally in this case. Therefore, the optimal design choice in terms of speed is governed by operational considerations.

Beam (B)

In Figure 8.7, the beam (B) of the vessel is plotted against the EEDI scores. The minimal total EEDI occurs at a beam of 53 meters. While the minimal construction EEDI occurs at a beam of 39 meters, its influence on the total EEDI is marginal, indicating that the beam choice is driven by operational efficiency rather than construction emissions. The ROI also shows an increase with the beam, with a maximum at a similar point as the minimal EEDI, confirming the alignment of ROI and EEDI minimization strategies.

Length (L)

Figure 8.8 illustrates the relationship between the vessel's length and the EEDI scores. The minimal operational EEDI occurs at a length of 213 meters, while the minimal construction EEDI is slightly smaller, occurring at the lowest length plotted meters. Again, construction emissions are a minor factor in the total EEDI calculation, meaning that length optimization is driven by operational considerations. The sharp decrease in ROI at lengths beyond 210 meters indicates that a longer vessel reduces profitability. The clear ROI optimum is most likely driven by the length at which the vessel exactly fits two monopiles behind eachother.

Depth (D)

In Figure 8.9, the depth (D) of the vessel is analyzed. The minimal total EEDI occurs at a depth of 16.5 meters, which is also the point of minimal construction EEDI. Interestingly, both operational and construction EEDI reach their minima at the same depth, suggesting that depth is a parameter where construction and operational emissions are aligned in their influence on the total EEDI score. This makes depth an important consideration in vessel design, as it affects both lifecycle emissions and operational performance.

8.5.4. Conclusions on the HFO Case

The analysis reveals that while construction emissions have distinct minimal points for some parameters, their overall contribution to the total EEDI score is small in the case of HFO. This means that design decisions, such as the optimal speed, length, beam, and depth, are largely influenced by operational efficiency rather than construction-related emissions. Given the dominance of operational emissions, the minimal EEDI performance for each parameter should prioritize reducing fuel consumption and improving operational efficiency. The alignment between minimal EEDI points and maximum ROI further confirms that energy-efficient designs also tend to be the most profitable.

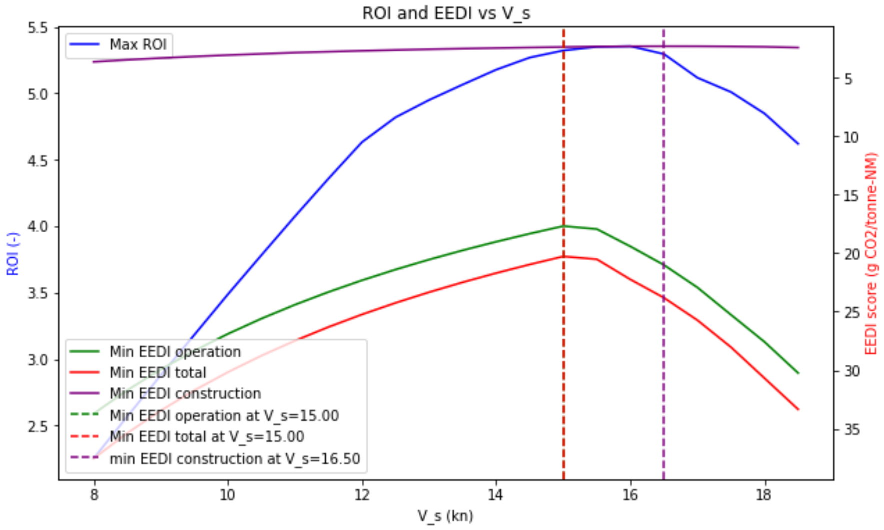


Figure 8.6: ROI, EEDI vs V_s

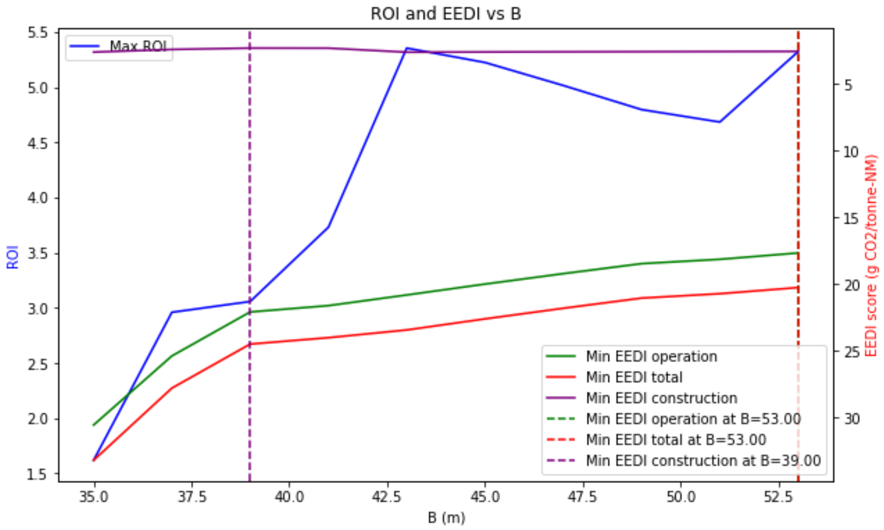


Figure 8.7: ROI, EEDI vs Beam

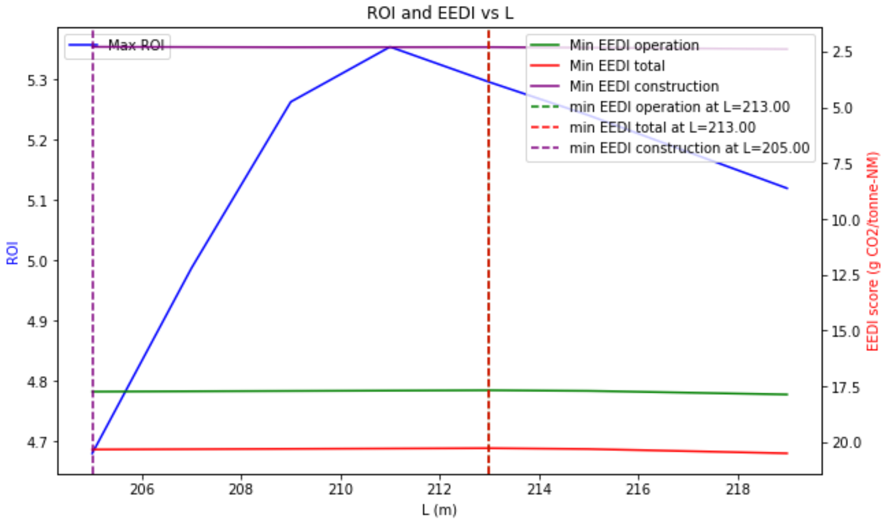


Figure 8.8: ROI, EEDI vs Length

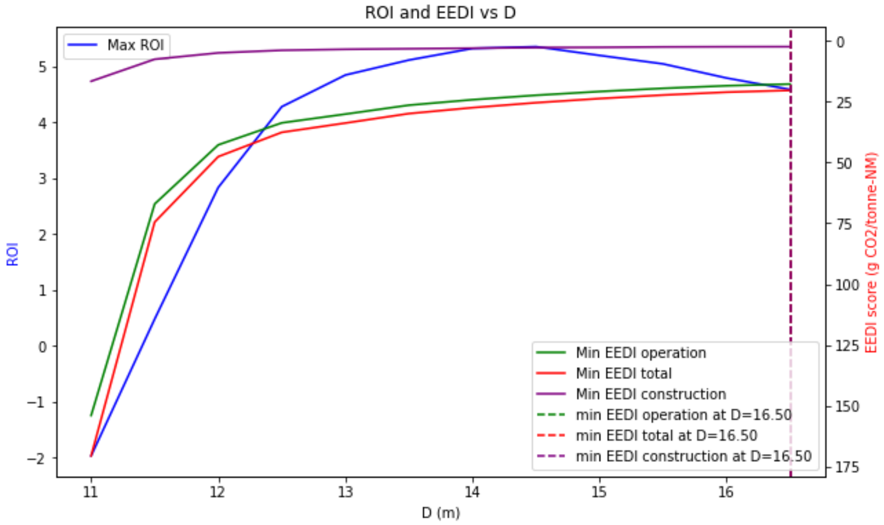


Figure 8.9: ROI, EEDI vs Depth

8.5.5. Effect of Design Parameters on EEDI and ROI Performance

The irregularities observed in some of the lines within the figures in this chapter can be attributed to a combination of factors related to design optimization and the complex interactions between various design parameters. Two main explanations emerge for these variations: the influence of optimal points for different design parameters and the underlying implications of these parameters on vessel performance.

Firstly, the influence of different design parameters, such as depth, beam, and length, on both EEDI and ROI can lead to shifts in the optimal performance points for these metrics. When considering the impact of depth, both EEDI and ROI are highly sensitive to changes in depth due to its direct effect on the maximum allowable propeller diameter and the vessel's cargo-carrying capacity. A greater depth allows for a larger propeller, which can improve propulsion efficiency and reduce fuel consumption, thereby lowering the EEDI score. Simultaneously, depth influences the vessel's ability to carry larger or heavier cargo, impacting both its operational flexibility and stability. These factors are critical in maximizing ROI, as increased cargo capacity can lead to greater revenue, while maintaining stability ensures the safe and efficient transport of cargo. Therefore, the depth parameter plays a dual role:

affecting the vessel's propulsion potential and its ability to meet commercial and operational objectives, making it a key determinant in both EEDI and ROI optimization.

Moreover, these trade-offs are often influenced by external constraints, such as the size and type of the cargo being transported. A higher depth may be advantageous for carrying heavier, more stable loads but may limit the flexibility of the vessel in shallow waters, influencing its mission profile and economic feasibility. Similarly, a reduced draft might enhance flexibility in navigating shallow waters, but it could compromise fuel efficiency and cargo stability, especially for larger monopiles or similarly bulky items.

Therefore, the irregularities observed in the EEDI and ROI performance graphs reflect the complex interplay between trying to optimize for operational efficiency, regulatory compliance (EEDI) while keeping a viable design. Figures 8.10a and 8.10b illustrate the relationship between the EEDI scores and vessel speed (V_s) across different depth values (D). These plots are an example of the influence of specific design parameters (in this case, speed and depth) on both lifecycle CO2 emissions and ROI. Similar analyses could be conducted to investigate the influence of other design parameters, such as beam, length, or displacement, providing valuable insights to inform vessel design decisions based on both environmental and economic factors.

EEDI LCA vs V_s for Different D Values

Figure 8.10a focuses on the **EEDI LCA** score, which incorporates lifecycle emissions (construction, operation, etc.) into the calculation. The plot demonstrates the effect of vessel speed on the lifecycle CO2 emissions for various depth values:

- **EEDI LCA Increases with Speed**: For all depth values, the EEDI LCA score shows a steady increase as vessel speed increases. This reflects the fact that higher speeds require more energy, leading to greater emissions over the lifecycle.
- **Effect of Depth (D)**: The plot shows distinct layering by depth value, with higher depth generally resulting in higher EEDI LCA scores. Specifically, the depth values *D = 14* and *D = 15* produce the highest EEDI scores, while *D = 11* and *D = 12* lead to lower overall scores. This suggests that vessels with lower depths are more efficient in terms of lifecycle CO2 emissions at higher speeds..

EEDI vs ROI for Different D Values

Figure 8.10b compares the **EEDI score** (not including lifecycle emissions) with the **ROI**, providing insights into the trade-offs between environmental and economic performance:

- **Inverse Relationship Between EEDI and ROI**: In general, the EEDI score decreases as the speed increases, while the ROI increases with speed. This inverse relationship highlights the typical trade-off between energy efficiency (environmental performance) and operational profitability (economic performance).
- **Effect of Depth (D)**: Similar to the previous plot, higher depths (*D = 14* and *D = 15*) lead to higher EEDI scores. Interestingly, these higher depth values also correspond to a lower ROI, indicating that designs with larger depths are less efficient both environmentally and economically.
- **Optimal ROI**: The plot shows that the maximum ROI is achieved at around 17-18 knots for all depth values, with the best-performing designs (in terms of ROI) occurring for lower depth values (*D = 11* and *D = 12*). This suggests that the most economically efficient designs are those that balance lower depths with optimal operational speeds.

8.5.6. Design Implications

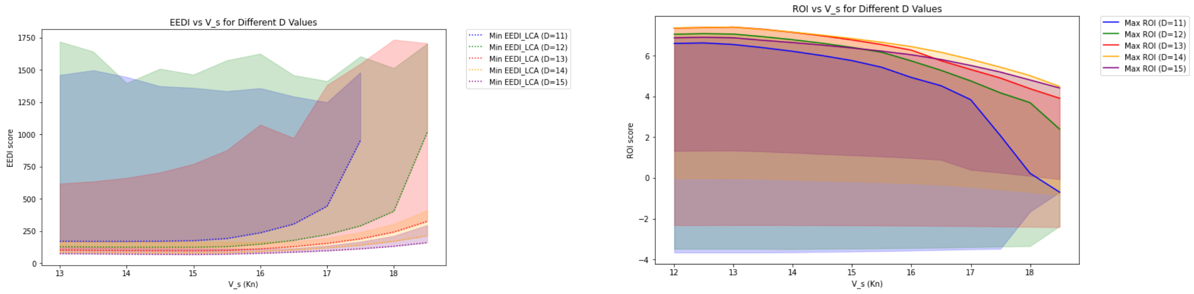
The analysis of the plots provides several key insights regarding vessel design:

- **Lower depths** (*D = 11, 12*) yield better overall environmental performance, with lower EEDI scores, and also result in higher ROI, making them ideal from both an environmental and economic perspective.
- **Higher depths** (*D = 14, 15*) are less efficient, leading to higher lifecycle emissions and lower ROI. These designs tend to be less favorable for both operational profitability and environmental impact.

- **Balancing Speed and Depth**: Achieving the optimal vessel design requires careful consideration of both speed and depth. While higher speeds improve ROI, they also increase emissions. Designers must strike a balance between these parameters to ensure that vessels meet both economic and environmental performance goals.

8.5.7. Final remarks

The irregular behavior which can be observed in some plots in the total EEDI line, with sudden shifts or corners, can be attributed the different EEDI performance of different values within a parameter. Just as shown in the plots, different curves could exist besides eachother for different values for depth or other parameters. Plotting the minimum EEDI within the design space would therefore result in a concatenation of the top parts of these different trends, resulting in an irregular line. Besides, influence of these parameters on the cargo capacity, propeller dimensions or other parameters would lead to sudden steps in the lines plotted.



(a) EEDI LCA vs V$_s$ and D values

(b) EEDI ROI vs V$_s$ and D values

Figure 8.10: Comparison of EEDI LCA and ROI as a function of V$_s$ and D values

8.6. Case Studies

This section explores several case studies to assess the impact of incorporating Life Cycle Assessment (LCA) in ship design decisions. By considering different scenarios, these case studies demonstrate how LCA influences both environmental performance and financial outcomes in the maritime industry. The following case studies examine the effects of variations in steel sourcing emissions, operational emissions, and the potential impact of a CO_2 tax on overall design strategy and vessel performance.

Each case study is analyzed with respect to its impact on EEDI, Return on Investment (ROI), and total lifecycle emissions, illustrating the importance of incorporating LCA in early-stage ship design to optimize both environmental and economic performance. The missions chosen to analyze is the vessel being used as HTV on the route Rotterdam - Beijing.

8.6.1. Steel Sourcing Regional Influence

Analysis of how steel sourcing impacts emissions, taking into account regional carbon intensities and sourcing methods. India is taken as case study, as the steel emissions are considerably higher than in china, the case so far considered (India 3.8 tonnes co2/tonne steel, China 1.84 tonne co2/tonne steel in 2022).

8.6.2. Case Study: India vs China Steel Production Emissions

This section provides a comparative analysis of EEDI and ROI results when considering higher emissions from steel production in India compared to China. The plots shown represent the case for India, where the carbon intensity of steel production is significantly higher. Specifically, steel production carbon intensity in India is around 3.8 tonnes CO2 per tonne of steel, whereas in China, that intensity is only 1.84 tonnes CO2 per tonne of steel [101]. The China case, previously analyzed, serves as a baseline with lower construction-related emissions. The design space parameters considered in this case are as follows:

- **Length (L)**: 200 to 230 meters, in increments of 2 meters.

- **Beam (B)**: 30 to 55 meters, in increments of 2 meters.
- **Depth (D)**: 10 to 17 meters, in increments of 0.5 meters.
- **Speed (V_s)**: 12 to 19 knots, in increments of 0.5 knots.
- **Mission**: HTV on route Rotterdam - Beijing.
- **DP Capability**: 70% of full DNV spectrum.
- **Block Coefficient (CB)**: 0.45 to 0.90, in increments of 0.05.
- **Fuel Type**: HFO (Heavy Fuel Oil).
- **Lifetime**: 30 years.
- **Origin of steel**: India.
- **Maintenance interval**: 5 years.

Speed (V_s)

Looking at Figure 8.11 (ROI and EEDI vs V_s):

- **Trend in EEDI and ROI**: The plot indicates that as the vessel speed increases, the total EEDI initially decreases, reaching a minimum at 15.0 knots, and then starts increasing again. The operational EEDI similarly decreases up to about 15 knots. Construction EEDI shows a different behavior, with a minimum at around 16.5 knots.
- **ROI Maximization**: The ROI peaks around 16 knots and then declines at higher speeds. This alignment between ROI and operational EEDI shows that the economic and environmental optimal speed is around 16 knots. However, as the total EEDI continues increasing beyond this point, the trade-off between profitability and environmental performance becomes significant.

Beam (B)

In Figure 8.12 (ROI and EEDI vs Beam):

- **EEDI and Beam**: The total EEDI score is lowest around a beam of 53 meters, while the operational EEDI remains mostly stable as the beam increases. The construction EEDI decreases slightly, reaching its minimum at 39 meters.
- **ROI Trends**: The ROI reaches its maximum at two points, being approximately 43 and 52 meters, confirming that larger beams are favorable in terms of profitability and environmental performance, but beyond a certain point, the efficiency gains decrease.

Length (L)

In Figure 8.13 (ROI and EEDI vs Length):

- **Length Influence**: The total EEDI score reaches its minimum at around 213 meters, where operational EEDI is also minimized. Construction EEDI reaches a minimum at 205 meters.
- **ROI**:The ROI reaches its peak at around 211 meters, indicating that vessels designed to fit two monopiles longitudinally behind each other have the highest ROI.

Depth (D)

In Figure 8.14 (ROI and EEDI vs Depth):

- **EEDI and Depth**: Both the total, construction and operational EEDI scores reach their lowest point at a depth of around 16.5 meters.
- **ROI**: The ROI is highest at a depth of approximately 14 meters, which aligns well with the minimum operational and construction EEDI points. This suggests that optimizing the depth to around 14-15 meters provides the best balance between environmental impact and profitability.

8.6.3. Design Implications Based on the Plots

From the analysis of the figures, the following key insights are derived:

- **Speed (V_s)**: The optimal speed for environmental performance and profitability is around 15.5-16 knots. Beyond this point, the total EEDI increases, especially driven by operational impacts.
- **Beam (B)**: A beam of approximately 53 meters optimizes total EEDI, while a beam around 43 meters maximizes ROI.
- **Length (L)**: The optimal length for minimal EEDI is around 213 meters, with ROI maximized slightly earlier at 205 meters.
- **Depth (D)**: The optimal depth for both EEDI and ROI is around 16-16.5 meters, demonstrating that depth is a key factor in optimizing both profitability and lifecycle emissions.

8.6.4. Effect of Higher Steel Emissions on EEDI and Design Considerations

The increased emissions from Indian steel production have no clear impact on the total EEDI or the optimization process. Operational emissions remain the largest contributor, and the higher steel sourcing emissions in India do not affect the identification of the optimal design points. Both the Pareto front and the design parameters, such as beam and speed values, remain entirely unchanged when comparing the India and China cases.

8.6.5. Conclusions on the India Steel Case

In conclusion, the higher emissions from steel production in India do not alter the lifecycle emissions profile or the resulting optimal vessel designs. The analysis confirms that operational efficiency continues to dominate design decisions, with no visible differences in the optimization outcomes between the India and China cases.

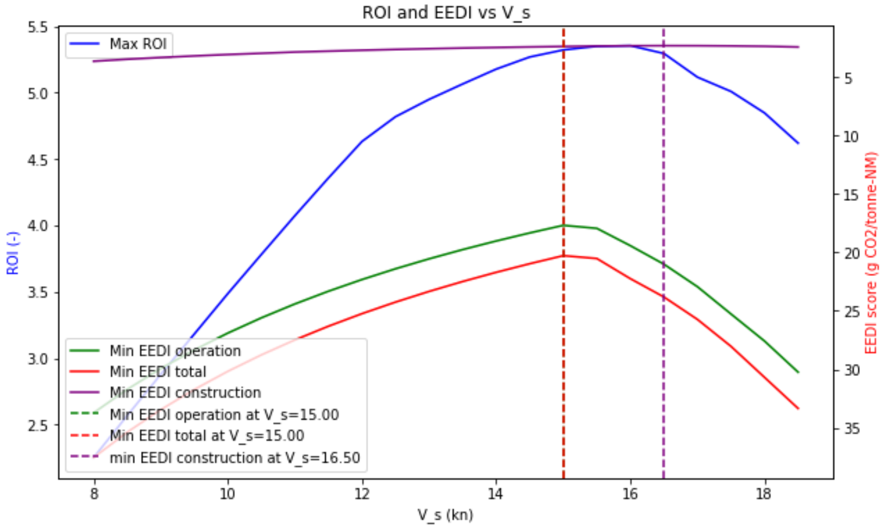


Figure 8.11: ROI and EEDI vs V_s

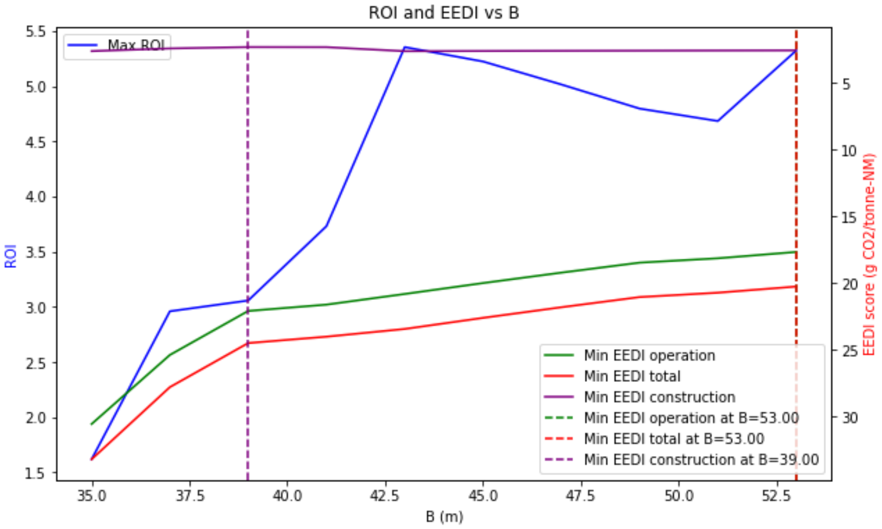


Figure 8.12: ROI and EEDI vs Beam

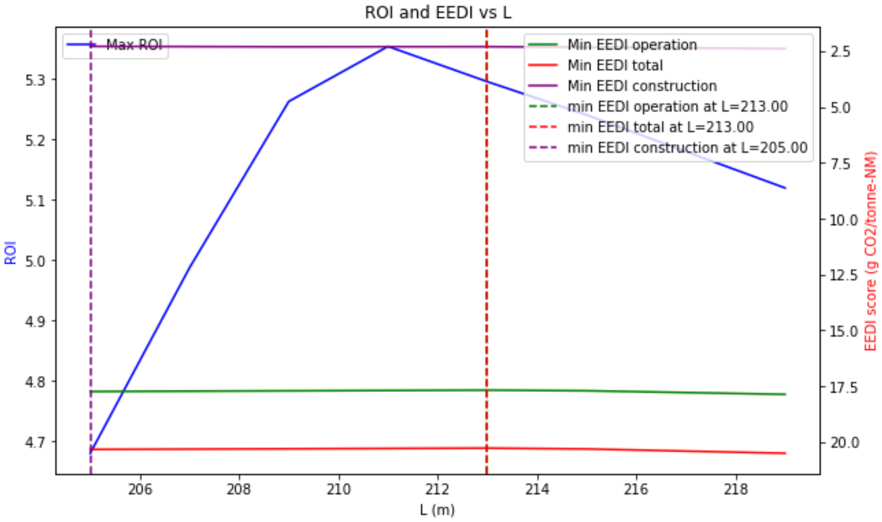


Figure 8.13: ROI and EEDI vs Length

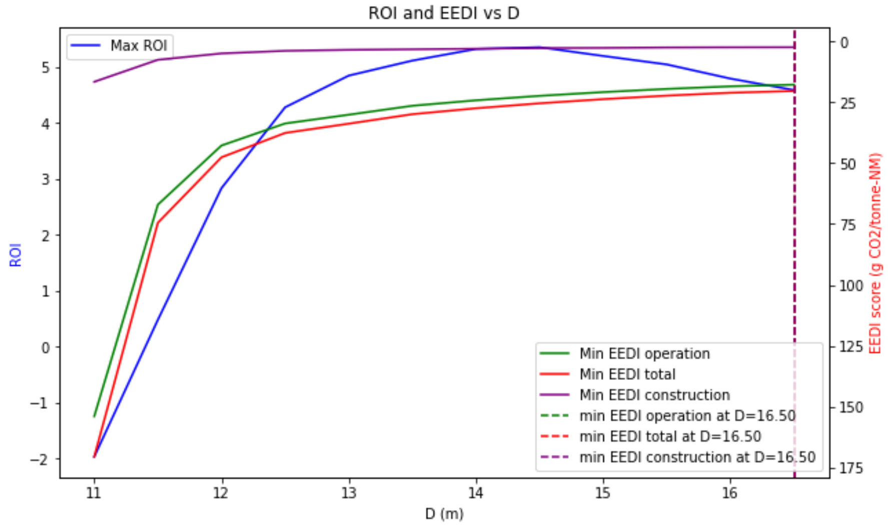


Figure 8.14: ROI and EEDI vs Depth

Here is a refined section that analyzes the plots for the methanol case (or reduced operational emissions) and emphasizes how lifecycle analysis (LCA) affects design choices:

8.7. Reduced Emissions Case

This section analyzes the impact of reduced operational emissions, such as when using methanol as an alternative fuel, on the EEDI and ROI for vessel designs. In this case, operational emissions are reduced to 5% of the levels seen with conventional HFO fuel, corresponding with green methanol with pilot fuel. The following figures illustrate the influence of vessel speed, beam, length, and depth on both the Energy Efficiency Design Index (EEDI) and return on investment (ROI). A key takeaway from this analysis is that when considering lifecycle emissions (including construction emissions), the optimal design parameters shift compared to when only operational emissions (EEXI) are considered.

The design space used is as follows

- **Length (L)**: 200 to 230 meters, in increments of 2 meters.
- **Beam (B)**: 30 to 55 meters, in increments of 2 meters.
- **Depth (D)**: 10 to 17 meters, in increments of 0.5 meters.
- **Speed (V_s)**: 12 to 19 knots, in increments of 0.5 knots.
- **Mission**: HTV on route Rotterdam - Beijing.
- **DP Capability**: 70% of full DNV spectrum.
- **Block Coefficient (CB)**: 0.45 to 0.90, in increments of 0.05.
- **Fuel Type**: Methanol with pilot fuel
- **Lifetime**: 30 years.
- **Origin of steel**: China.
- **Maintenance interval**: 5 years.

8.7.1. Speed (V_s)

In Figure 8.15, the relationship between vessel speed and EEDI/ROI is examined under reduced operational emissions.

Key trends:

- **Operational EEDI**: The green line (EEDI operational) remains relatively flat, demonstrating that operational emissions, now significantly reduced by using methanol, are no longer the primary factor in determining the EEDI.
- **Total EEDI**: The total EEDI (red line) is now heavily influenced by the construction phase, and the minimum value occurs at around 15.5 knots, compared to lower speeds in the HFO case. This shift is because construction emissions now form a larger proportion of the overall lifecycle emissions.
- **Construction EEDI**: The construction EEDI (purple line) plays a much more significant role. As seen from the plot, it remains steady across speeds, highlighting that the total EEDI is largely driven by the construction emissions in this scenario.
- **ROI**: The blue line representing ROI shows the usual increasing trend with speed, reaching its peak around 16 knots. Since the operational emissions are drastically lower, speed optimization for profitability remains aligned with low emissions, but total lifecycle emissions must be considered more closely.

8.7.2. Beam (B)

Figure 8.16 shows the influence of beam on EEDI and ROI under reduced operational emissions.

Key trends:

- **Operational EEDI**: Similar to the speed analysis, the operational EEDI stays relatively flat across the range of beams due to the lowered operational emissions from methanol.
- **Total EEDI**: The minimum total EEDI shifts towards a beam of around 41 meters, compared to the wider beam seen in the HFO scenario. The higher contribution of construction emissions causes narrower beams to become more favorable in reducing the total lifecycle impact.
- **Construction EEDI**: The construction EEDI maintains a stable profile, as construction emissions are directly tied to the beam size and remain largely unaffected by operational factors.
- **ROI**: As in previous cases, the ROI continues to increase with beam size, with maximum ROIs around 43 and 53 meters. However, in a lifecycle perspective, the choice of beam should also minimize construction emissions, leading to different trade-offs.

8.7.3. Length (L)

In Figure 8.17, the relationship between vessel length and EEDI/ROI is explored.

Key trends:

- **Operational EEDI**: The operational EEDI remains nearly constant across the range of lengths, as operational emissions have been significantly reduced and are no longer a major driver of emissions.
- **Total EEDI**: The total EEDI shows its minimum at around 205 meters, reflecting a balance between construction and reduced operational emissions.
- **Construction EEDI**: Similar to the previous parameters, the construction EEDI remains flat and dominates the total EEDI, making lifecycle emissions a key design consideration.
- **ROI**: The maximum ROI is observed at a length of around 211 meters, indicating that while profitability may increase with length, designers must account for construction emissions to achieve an environmentally optimal design.

8.7.4. Depth (D)

Figure 8.18 presents the impact of vessel depth on EEDI and ROI under reduced operational emissions.

Key trends:

- **Operational EEDI**: The operational EEDI shows little variation across the range of depths due to the minimal contribution of operational emissions in this case.

- **Total EEDI**: The total EEDI is minimized at a depth of 16.5 meters, similar to the HFO scenario. However, the lower operational emissions make the total EEDI more sensitive to construction emissions.
- **Construction EEDI**: The construction EEDI is stable across depths, indicating that construction emissions now form a larger share of the total lifecycle impact.
- **ROI**: The ROI reaches its peak at a depth of around 14 meters, aligning closely with the depth at which total EEDI is minimized. This alignment shows that lifecycle optimization can result in designs that are both profitable and environmentally efficient.

8.7.5. Remarks on EEDI and ROI Optima: a new 'Champion'

The analysis of the figures reveals key insights regarding the optimal design choices based on different EEDI components (operational, construction, and total):

- **Different Optima for Different EEDI Components**: Each EEDI score (operational, construction, total) exhibits different optimal points for key design parameters such as speed, beam, length, and depth. These differences highlight that optimizing for one phase (e.g., operational) does not necessarily lead to optimal lifecycle emissions when construction and other lifecycle factors are considered.
- **Impact of Including Full LCA**: The inclusion of construction emissions in the total EEDI alters the optimal design parameters compared to when only operational emissions are considered. For instance, in cases where operational emissions dominate (as in conventional fuel scenarios), designs might prioritize higher speeds or larger vessels. However, when construction emissions are accounted for, design decisions may shift toward lower speeds or smaller vessels to reduce total lifecycle impacts.
- **Contrasting ROI with EEDI Optima**: The maximum ROI does not always align with the minimum total EEDI, especially when including lifecycle emissions. This suggests that designing for profitability alone can lead to suboptimal environmental outcomes if the full LCA is not considered.
- **Design Implications**: To achieve an environmentally optimized vessel design under full LCA, an analysis must be made of both operational efficiency (as reflected by the operational EEDI) and minimizing construction-related emissions (as reflected by the construction EEDI). This trade-off becomes crucial when aiming at designing vessels with the lowest emissions from a full lifecycle perspective running on alternative fuels, such as methanol, that drastically reduce operational emissions.

Design with Lowest Operational EEDI

The design that minimizes operational EEDI focuses primarily on reducing emissions during the vessel's operation phase. For this, the following design characteristics are preferred:

- **Vessel Speed (V_s)**: As shown in Figure 8.15, the lowest operational EEDI is achieved at a vessel speed of approximately **15.0 knots**. This speed strikes a balance between fuel efficiency and transport work (tonne-nautical mile), minimizing emissions for the given mission.
- **Beam (B)**: The optimal beam for the lowest operational EEDI occurs around **53 meters**, as indicated in Figure 8.16. A wider beam typically reduces resistance, improving fuel efficiency during operation.
- **Length (L)**: For the lowest operational EEDI, the vessel length is around **213 meters** (see Figure 8.17). This longer length reduces drag, contributing to improved operational efficiency.
- **Depth (D)**: The optimal depth for operational EEDI is **16.5 meters**, according to Figure 8.18. A higher depth and a corresponding higher draft often improves hydrodynamic performance, which in turn lowers fuel consumption during operation.

This design prioritizes hydrodynamic efficiency, larger dimensions, and moderate speeds to minimize emissions during the operational phase. However, it does not take into account the emissions associated with building or maintaining these larger structures.

Design with Lowest LCA EEDI

The lowest LCA EEDI design, on the other hand, takes into consideration emissions from the entire lifecycle of the vessel, including construction, operation, and decommissioning. As a result, the optimal design characteristics differ:

- **Vessel Speed (V_s)**: For the lowest total (LCA) EEDI, the optimal speed is around **16.5 knots**, as seen in Figure 8.15. This speed is slightly higher than the operational EEDI minimum, balancing operational efficiency with lifecycle emissions.
- **Beam (B)**: The design with the lowest LCA EEDI favors a beam of **41 meters**, according to Figure 8.16. A smaller beam reduces construction material requirements, leading to lower emissions during the building phase.
- **Length (L)**: The length that minimizes the LCA EEDI is around **205 meters**, as shown in Figure 8.17. A shorter length reduces construction emissions while still allowing for operational efficiency.
- **Depth (D)**: The lowest LCA EEDI is achieved with a depth of **16.5 meters**, as shown in Figure 8.18. This remains consistent with the operational EEDI, showing that depth is a critical factor in both lifecycle and operational efficiency.

This design favors more moderate dimensions and a slight reduction in size (compared to the operational EEDI design) to reduce emissions associated with material use during construction, without sacrificing too much in terms of operational efficiency.

Key Differences Between Operational EEDI and LCA EEDI Designs

- **Beam**: The largest difference is in the beam. The lowest LCA EEDI design favors a narrower beam (**41 meters**) compared to the lowest operational EEDI design (**53 meters**). The larger beam reduces operational fuel consumption but increases construction emissions, leading to different optima depending on the goal.
- **Length**: Similarly, the lowest LCA EEDI favors a shorter length (**205 meters**) compared to the operational design (**213 meters**). Again, this reduces material use in construction but slightly increases drag during operation.
- **Speed**: The lowest LCA EEDI speed (**15.5 knots**) is slightly higher than the optimal operational EEDI speed (**15.0 knots**). This indicates that a slight increase in speed balances lifecycle emissions more effectively.

8.7.6. Conclusion

The different show the added value of taking into account a whole lifecycle perspective when design for the lowest lifetime CO2 emissions in certain cases. In this reduced operational emissions case, the inclusion of lifecycle emissions into the EEDI calculation shifts the design optima compared to scenarios that consider only operational EEXI. When operational emissions are minimized, the design parameters that reduce lifecycle construction emissions become increasingly important. This analysis emphasizes that designers must consider the full lifecycle, including construction impacts, to achieve the lowest environmental impact of a low operational emission design while maintaining economic viability. Only by doing this, the true lowest CO_2 emission 'champion' is found.

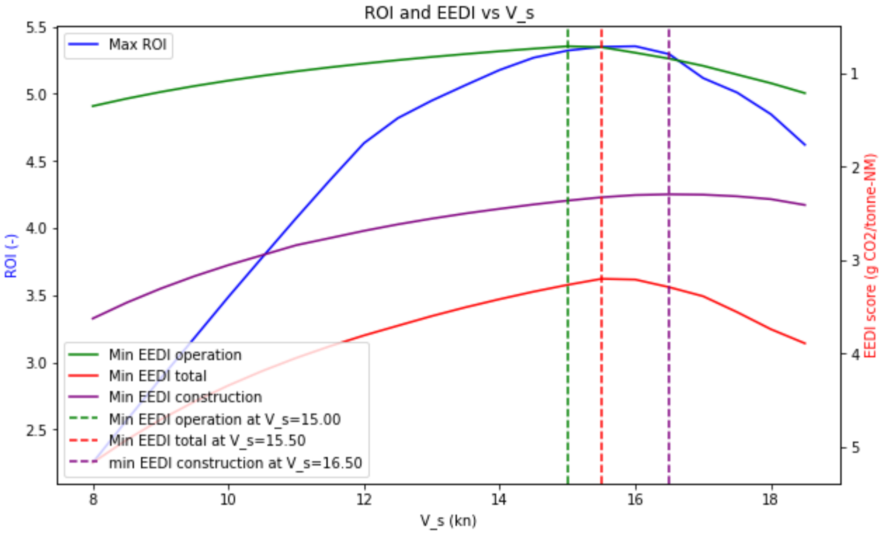


Figure 8.15: Effect of vessel speed (V_s) on ROI, operational EEDI, construction EEDI, and total EEDI in the reduced operational emissions case.

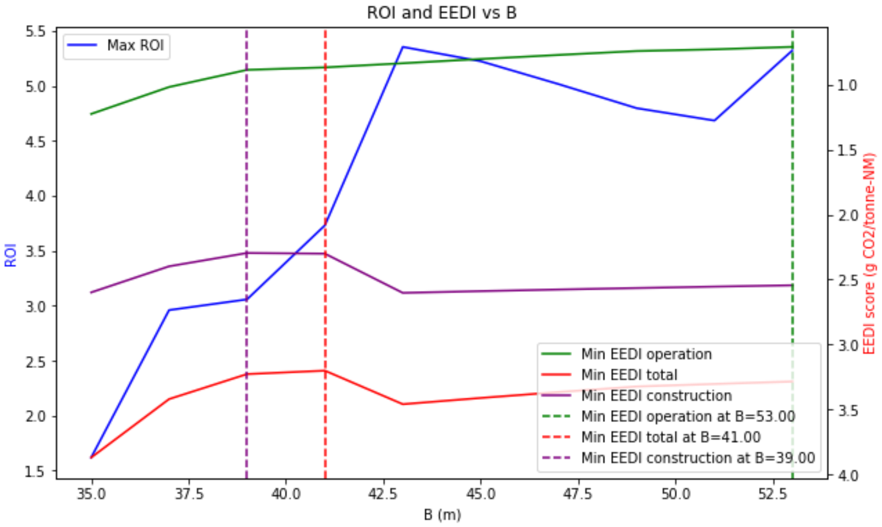


Figure 8.16: Effect of beam (B) on ROI, operational EEDI, construction EEDI, and total EEDI in the reduced operational emissions case.

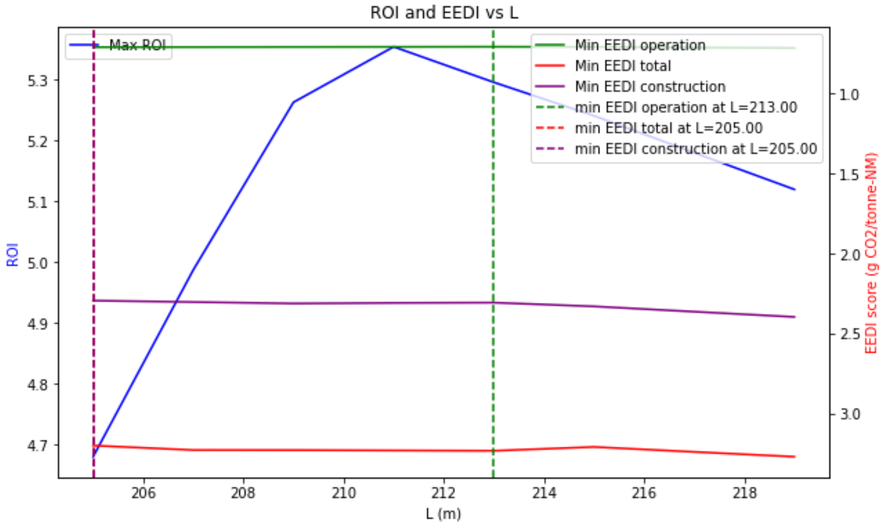


Figure 8.17: Effect of length (L) on ROI, operational EEDI, construction EEDI, and total EEDI in the reduced operational emissions case.

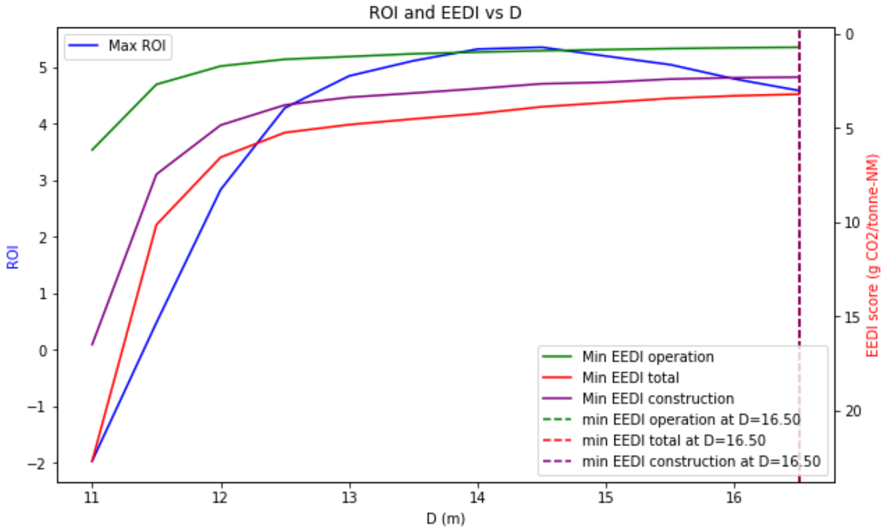


Figure 8.18: Effect of depth (D) on ROI, operational EEDI, construction EEDI, and total EEDI in the rreduced operational emissions case.

8.8. Influence on CO_2 Tax

The introduction of a CO_2 tax directly affects the financial performance of a vessel's operation by penalizing higher emissions with increased operational costs. However, this tax does not have a direct influence on the Energy Efficiency Design Index (EEDI) score, which is based on the physical design characteristics of the vessel and its operational efficiency in terms of fuel consumption and emissions per transport work.

Effect on ROI

The ROI (Return on Investment) is strongly influenced by the implementation of a CO_2 tax, especially in emission-intensive fuels such as Heavy Fuel Oil (HFO). With a CO_2 tax, the operational cost increases proportionally to the amount of CO_2 emitted, leading to a reduced ROI, particularly for designs with higher operational emissions. In contrast, vessels operating with alternative fuels, such as methanol or LNG, which produce lower CO_2 emissions, would benefit from a lower tax burden and thus maintain a higher ROI.

As a result, vessel designs that are more environmentally friendly—either through more efficient operational profiles or the use of low-carbon fuels—will become more financially attractive in the long term. The following key effects can be observed:

- **Higher Penalty for Emission-Intensive Fuels**: Vessels using high-emission fuels will experience a significant reduction in ROI as the CO_2 tax adds to the cost of operation. This makes fuel choices that produce fewer emissions, such as methanol or LNG, more financially viable.
- **Influence on Design Choices**: With a CO_2 tax, designs optimized for lower fuel consumption and emissions (reflected by lower operational LCA EEDI) will see a proportionally smaller impact on ROI. This may incentivize shipowners and designers to adopt more efficient technologies or operational strategies to minimize the financial burden of the tax.
- **Long-Term Financial Benefits for Low-Emission Designs**: Ships designed with lifecycle emissions in mind, including considerations for lower operational CO_2 emissions, will have an improved financial profile in a scenario where CO_2 taxes are implemented, leading to better long-term ROI compared to high-emission counterparts.

Impact on ROI for the low emission case

To further demonstrate the limited influence of a CO_2 tax on the outcomes, particularly for the low-emission case, Figure 8.19 illustrates the impact of different CO_2 tax values on ROI. In the low-emission scenario, the overall CO_2 emissions are significantly lower, which reduces the effect of a CO_2 tax on the ROI. As shown in the figure, the variation in ROI across different CO_2 tax levels is minimal, indicating that the emission profile across varying sailing speeds (V_s) remains relatively constant. This results in a negligible impact on ROI, even with different tax rates, confirming that for low-emission operations, ROI remains stable and largely unaffected by the imposed CO_2 tax.

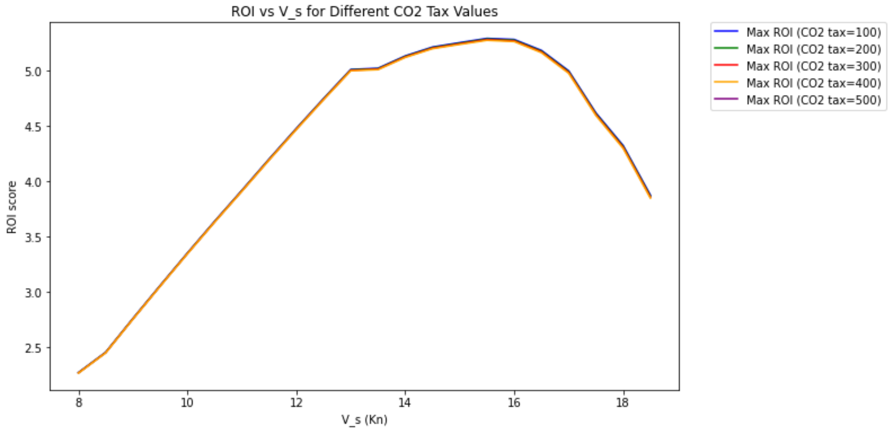


Figure 8.19: Influence of CO2 tax on ROI for the low emission case

No Direct Impact on EEDI

The EEDI is calculated based on a vessel's fuel consumption and CO_2 emissions per tonne-nautical mile but does not factor in any economic aspects such as taxes or operational costs. As a result, the CO_2 tax, while affecting the financial performance of a vessel, does not alter the EEDI score.

This distinction highlights the fact that while the EEDI provides a measure of a vessel's energy efficiency and its environmental impact in terms of emissions, it remains purely a technical metric. In contrast, ROI is a financial measure, and thus the two metrics can behave independently in response to policy measures such as CO_2 taxes.

Key Points:

- The **EEDI score remains unchanged** regardless of a CO_2 tax, as it is purely a measure of technical efficiency and emissions per transport work.
- A CO_2 tax would primarily affect **ROI**, penalizing designs with higher operational emissions and favoring vessels using cleaner, lower-emission fuels.

- **Design implications**: When both EEDI compliance and ROI are considered, a CO_2 tax incentivizes designs that not only meet EEDI requirements but also minimize financial exposure to emissions-related costs.

Concluding Remarks on CO_2 Tax Influence

In conclusion, while a CO_2 tax does not directly influence the EEDI score, it has significant implications for the financial attractiveness of vessel designs. Designs that focus on reducing lifecycle emissions, particularly through the use of alternative fuels or more efficient operational profiles, are better positioned to maintain profitability under such regulatory measures. This highlights the growing importance of integrating both environmental and economic considerations into the design process to ensure optimal vessel performance in both technical and financial terms.

8.9. Conclusion

This chapter addressed research questions 4, 5, and 6, offering valuable insights into how a full lifecycle optimization in *Blended Design* affects early-stage vessel design and the impact of shipbuilding and decommissioning on greenhouse gas (GHG) emissions and cost outcomes.

Research Question 4: Full Lifecycle Optimization performance in Blended and influence on design decisions

The results demonstrate that a full lifecycle optimization in *Blended* could lead to significant shifts in design choices. When lifecycle emissions are considered in addition to operational efficiency, optimal designs are no longer driven solely by fuel consumption and speed but also by material sourcing and construction-related emissions. This change in focus promotes more balanced designs that reduce both operational and construction emissions.

Research Question 5: GHG Emissions Impact from Shipbuilding and Decommissioning

The lifecycle analysis (LCA) results indicate that while operational emissions remain the dominant contributor to total emissions, shipbuilding, particularly the material sourcing phase, can contribute up to 10% of the overall lifecycle emissions. The impact of decommissioning, although smaller, also adds to the overall environmental footprint. Therefore, early-stage design decisions that minimize material use or favor low-emission materials can substantially reduce a vessel's lifecycle GHG emissions, underscoring the importance of considering construction and decommissioning in design choices.

Research Question 6: Cost Impact from Shipbuilding and Decommissioning

The analysis showed that higher emissions during the shipbuilding phase, particularly from high-carbon steel sourcing, can lead to significant increases in lifecycle costs, especially when coupled with carbon pricing mechanisms like CO_2 taxes. The influence of shipbuilding on lifecycle costs becomes more apparent as operational emissions are reduced, making construction emissions a larger share of the total. This highlights the importance of integrating both environmental and economic considerations when optimizing vessel designs for cost-efficiency over their entire lifecycle.

In conclusion, these findings emphasize the need for a holistic approach in vessel design that includes lifecycle considerations. By integrating both environmental impacts and economic factors, designers can optimize for the lowest lifecycle emissions and costs, ensuring the design meets both sustainability goals and financial viability. The outcome of this optimization is different than one focused at the operational phase of the vessel only.

9

Validation

This chapter focuses on the validation of the emission breakdown and uncertainties introduced in the analysis. The goal is to assess how uncertainty impacts the final CO_2 emissions and whether this influences critical metrics like the Energy Efficiency Design Index (EEDI) or design decisions.

9.1. Reliability of Operational Emissions and Overall Data

One of the most critical components of the lifecycle emissions analysis is the operational phase, which, as demonstrated, accounts for the largest share of CO_2 emissions for heavy transport vessels using traditional fuels like HFO. The operational emissions have been extensively validated in earlier research, such as Zwaginga et al. (2021)[34] and Peeten (2022)[32], where similar methodologies have been applied to assess vessel fuel consumption, speed profiles, and overall operational efficiency. This validation provides a strong foundation for the operational emissions used in this study, ensuring that they are both accurate and reliable.

9.1.1. Validation of Operational Emissions

As operational emissions dominate the overall emissions profile of most vessels, ensuring their accuracy is paramount. Previous studies have employed detailed ship monitoring and fuel consumption data to calculate CO_2 emissions per nautical mile. This research follows a consistent methodology, incorporating well-established emission factors, vessel-specific power settings, and fuel type characteristics. The consistency of these methods with earlier works not only reinforces the validity of the operational emissions used but also indicates that these figures can be confidently used for further design and environmental assessments.

Given that operational emissions are based on validated empirical data, their uncertainty is effectively zero in the context of this study. This enhances the robustness of the results, as operational emissions drive the bulk of the EEDI score and overall environmental impact.

9.1.2. Data for Other Lifecycle Phases

For other phases of the vessel's lifecycle, such as construction, sourcing, maintenance, and end-of-life, the data is sourced from established literature, as outlined in Chapter 6. These values are derived from industry reports, lifecycle inventories, and regional emissions data, which provide a solid foundation for the lifecycle assessment. For example, the steel sourcing data leverages regional carbon intensity factors from sources such as Worldsteel (2020)[107] and the Joint Research Center of the EU (2022)[101], which are considered reliable and up-to-date.

Although these phases introduce some uncertainty into the overall emissions due to regional differences in steel production, maintenance practices, and recycling efficiency, the robust methods used in this study ensure that the impact of these uncertainties remains minimal. By consistently applying the same lifecycle assessment methodology, the outcomes maintain a high degree of reliability, even with the minor uncertainties present in the sourcing and construction phases.

9.1.3. Reliability of the Overall Outcome

Combining the validated operational emissions with data from reputable literature sources for other lifecycle phases ensures the overall reliability of the study's outcomes. The method used throughout the analysis follows a consistent and transparent framework, which allows for reproducibility and confidence in the results. Furthermore, the operational emissions' dominance means that the impact of uncertainties from other lifecycle phases is relatively small, reinforcing the robustness of the conclusions drawn from this analysis.

As the focus of this study shifts towards low-emission scenarios—such as vessels powered by methanol or other alternative fuels—the reliability of the outcomes continues to be supported by the thorough validation of operational emissions. In such cases, even though non-operational emissions take on a greater share, the use of established literature and validated methods ensures that the results remain trustworthy and can serve as a reliable guide for decision-making in vessel design and environmental impact reduction strategies.

9.2. Breakdown of CO_2 Emissions and Uncertainty

Figure 9.1 shows the breakdown of CO_2 emissions into different components, with uncertainties included. The plot highlights the contribution of sourcing, construction, maintenance, operation, and end-of-life processes to the total emissions. As seen, operational emissions dominate the total, which reduces the overall impact of uncertainty from the other components.

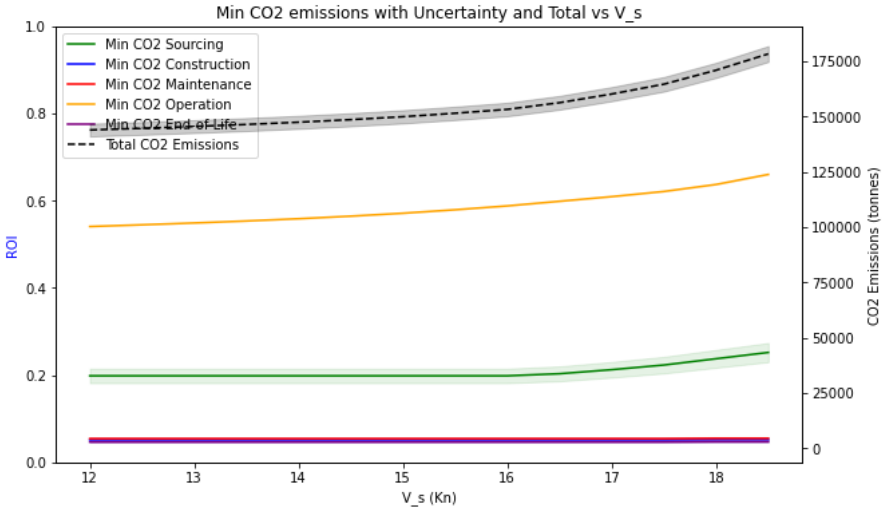


Figure 9.1: Breakdown of CO_2 emissions (Total and Min Values) vs Sailing Speed (V_s), including uncertainties

Despite varying levels of uncertainty across different components (sourcing, construction, maintenance, and end-of-life), the dominance of operational emissions ensures that the total uncertainty remains relatively small. This leads to a more robust assessment of total emissions, even when considering variations in regional sourcing or construction methods.

9.3. Influence on EEDI

Figure 9.2 shows the relationship between ROI and EEDI, along with uncertainty assumptions.

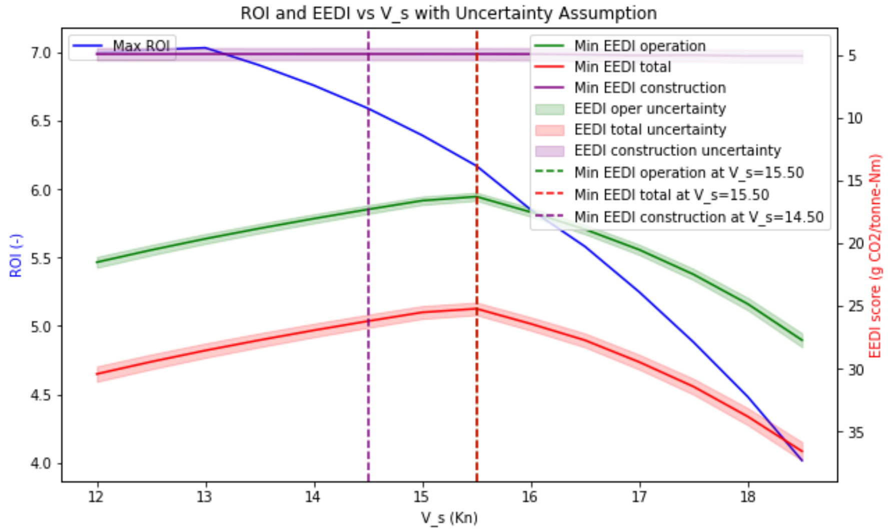


Figure 9.2: ROI and EEDI vs Sailing Speed (V_s) with Uncertainty Assumption

Low-emission cases are possible, as the vessel could sail on alternative fuels like methanol, so these are not edge scenarios. However, at different V_s, the impact of uncertainty remains limited because the contribution shares of the various emission components (e.g., sourcing, construction, operation) are similar across all V_s.

For other design parameters, the uncertainty would lead to a higher or lower contribution from the construction phase. In low-emission scenarios, this could result in an earlier shift of the optimal design towards the point where the construction EEDI reaches its minimum. This shift would occur because, in low-emission scenarios, the contribution of construction becomes relatively more significant as operational emissions decrease, influencing the overall design decision towards minimizing construction-related emissions.

9.4. Influence on Design Decisions

The analysis shows that in typical operating scenarios, the influence of uncertainty on design decisions remains small. The general shares of emissions from sourcing, construction, and maintenance are consistent across different design parameters such as sailing speed (V_s), length, beam, and depth. This suggests that design decisions driven by minimizing CO_2 emissions can largely ignore the uncertainties associated with these components. This can also be seen in figure 9.2, within the boundaries of the uncertainty the location of the optimum design for operational and full lifecycle emissions remains unaffected.

However, in low-emission cases or specific scenarios where non-operational emissions contribute significantly to the total (e.g., short missions with extensive time not sailing or high reliance on materials with uncertain sourcing emissions), uncertainty could influence design choices. This is particularly true when evaluating alternative materials, fuel types, or construction methods, where sourcing uncertainties may lead to different optimal designs.

9.4.1. Low Emission Case with Uncertainty

Figure 9.3 introduces uncertainty ranges for both operational and lifecycle EEDI scores for the low emission case. The shaded regions provide insight into how variability in emissions data and lifecycle impacts might influence optimal design choices.

The figure shows uncertainty in both the **operational EEDI** (green line with green shading) and the **total LCA EEDI** (red line with red shading). This uncertainty is critical to consider as it indicates that the true minima for each EEDI score could deviate from the calculated optima:

- **Operational EEDI**: The uncertainty in the operational EEDI score shows a range within which

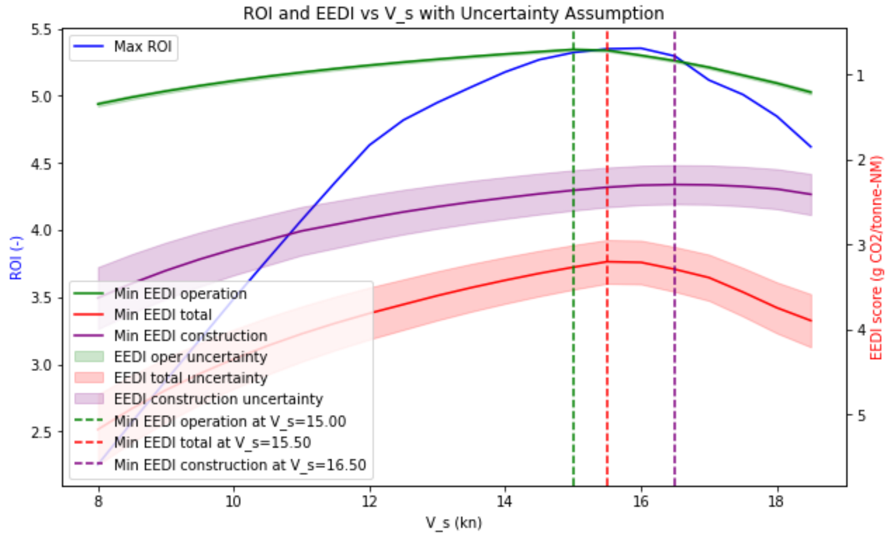


Figure 9.3: ROI and EEDI vs Sailing Speed (V_S) with Uncertainty Assumption for the low emission case

the true minimum may fall. While the calculated minimum occurs at approximately **15.5 knots**, the uncertainty region indicates that the true optimal speed for minimizing operational emissions could range between 15 and 17 knots.

- **LCA EEDI**: The total LCA EEDI, which accounts for lifecycle emissions, shows a wider range of uncertainty. The calculated minimum occurs at around **16 knots**, but the uncertainty suggests that the optimal speed could vary from 14 to 17 knots.
- **Construction EEDI**: The construction EEDI, while exhibiting some uncertainty (purple shading), continues to have a smaller influence on the overall design compared to operational and total LCA EEDI. However, as operational emissions are significantly reduced in the low-emission case, construction emissions become more relevant.

Effect on Design Choices

The presence of uncertainty implies that the calculated optimal design points (in terms of vessel speed) may not be as conclusive as initially assumed. For example, the analysis suggests that the lowest operational EEDI occurs at **15.5 knots**, but real-world variability could shift the optimal speed slightly higher or lower. Similarly, the optimal speed for the lowest total LCA EEDI, calculated at **16 knots**, might actually fall within a broader range due to the uncertainty.

Designers should therefore exercise caution when relying strictly on the calculated minima. The variability indicated by the uncertainty ranges means that seemingly optimal points could shift, and suboptimal designs might emerge if uncertainty is not accounted for. This underscores the need for robust design strategies that accommodate variability in emissions data and lifecycle impacts.

Conclusion on Uncertainty

In conclusion, the uncertainty illustrated in Figure 9.3 highlights the importance of flexibility in the vessel design process. Although the general trends and design insights remain valid, the uncertainty introduces a layer of complexity. The optimal design may vary within a range of speeds and other parameters, particularly for low-emission cases where operational emissions are minimized and construction emissions take on greater importance. Incorporating uncertainty analysis into the design process leads to more adaptable and environmentally resilient decisions.

9.4.2. Utopian points on the pareto front

An important consideration in this analysis is the verification of whether the proposed optimal design actually exists within the design space. Without such verification, there is a risk of identifying "utopian points," where the combination of parameters is theoretically optimal but practically unachievable. This has been checked, and it was found that the optimal design is not present in the design space for the case study in Chapter 8.7 due to the step size used in defining the design parameters. Not all possible combinations are captured within the existing design space. However, a design with a slightly higher speed or marginally different parameters does exist and achieves the same EEDI.

This highlights that additional designs could be generated with finer parameter increments to explore the exact configuration that would be truly optimal. Nonetheless, the case study demonstrates that design decisions are influenced by incorporating LCA considerations and that there are realistic, non-utopian designs capable of achieving the identified optimal values. This ensures the robustness of the conclusions drawn and the practical applicability of the findings.

9.5. Conclusion

The results demonstrate that while uncertainties exist, especially for sourcing and construction, their influence on total CO_2 emissions and critical metrics like EEDI is limited in most cases. The robustness of the operational emissions component ensures that the overall environmental impact remains consistent. Only in low-emission scenarios, where operational emissions are reduced, the uncertainties become more significant. This suggests that further research into the uncertainty of material sourcing and construction processes could be valuable for future low-emission vessel designs.

The data used for these calculations (see Chapter 6) are based on established literature values, ensuring that the results align with industry standards. Moving forward, these uncertainties can be reduced by incorporating more detailed lifecycle data and region-specific factors.

10

Discussion and Future work

This chapter provides both a discussion of the findings and suggestions for future work. The discussion focuses on the integration of Life Cycle Assessment (LCA) into the *Blended* Design tool from Ulstein Design and Solutions B.V., examining how incorporating non-operational phases such as construction, maintenance, and end-of-life affects vessel design decisions. While operational emissions remain the largest contributor, considering full lifecycle emissions offers a more comprehensive understanding of environmental impact.

Key uncertainties, such as variations in steel sourcing and maintenance emissions, are explored, highlighting their influence on design choices. Despite these uncertainties, operational efficiency remains a critical focus for most vessel designs, though the inclusion of lifecycle emissions introduces new considerations for sustainability.

In the future work section, recommendations are made for refining LCA data, incorporating circular economy principles, exploring extended vessel lifetimes, optimizing maintenance strategies, and fully integrating the LCA module into *Blended*. These steps aim to enhance the precision and sustainability of early-stage vessel design.

10.1. Discussion

This research has explored the integration of Life Cycle Assessment (LCA) into the early-stage design of offshore vessels, particularly within the *Blended* Design framework developed by Ulstein Design and Solutions B.V. The key challenge addressed was incorporating non-operational lifecycle phases—such as construction and end-of-life stages—into the existing ship design tool, which traditionally focused on operational performance. By expanding the scope of design optimization to consider full lifecycle emissions, this study has introduced new possibilities for achieving both economic and environmental sustainability in ship design.

The results indicate that incorporating LCA could influence design decisions, particularly in low-emission operational scenarios. While the inclusion of construction and maintenance emissions increases the overall carbon footprint, operational emissions remain the dominant factor, especially for Heavy Fuel Oil (HFO)-fueled ships. For such ships, the study shows that the primary focus should be on reducing operational emissions as they make up the largest share of the total lifecycle emissions.

However, the uncertainty surrounding construction emissions, particularly steel sourcing, demonstrates that design choices such as material selection and sourcing region can have notable impacts on the overall emissions profile. Sourcing steel from regions with higher carbon intensities, such as India or South Africa, can significantly affect the lifecycle emissions of a vessel. In contrast, sourcing from regions like the EU or China, where emissions are lower, offers an opportunity to reduce overall construction emissions.

One important realization is that low-emission operational designs may not always result in the most sustainable or cost-effective designs when considering the full lifecycle. This raises critical questions about the trade-offs between different lifecycle phases and their relative importance in the design process. Moreover, the study highlights that uncertainties, especially in construction and maintenance phases, do not drastically alter the relative importance of different design strategies for high-emission vessels but become more significant in low-emission operational designs.

An additional source of uncertainty arises because vessels that do not comply with the Carbon Intensity Indicator (CII) are not filtered out of the design space, as this criterion is not included in *Blended*. Consequently, designs may include vessels that would ultimately face operational or regulatory challenges. Furthermore, some carbon intensities, such as those from welding and cutting processes, are attributed to outputs from *Blended*, which are primarily based on weight estimates. This means that parameters like plate thickness, which could directly influence emissions from welding and cutting, are not explicitly modeled. These limitations introduce further variability in the attribution of emissions and highlight the need for more granular integration of construction-phase emissions in the design process.

Despite these uncertainties, the general shares of emissions per lifecycle phase remain relatively stable across different designs. This suggests that the influence of uncertainty, while not negligible, does not substantially change the overall design trajectory. The general trend is consistent across various design parameters like vessel speed (V_s), length, and depth, further confirming that design decisions focused on operational efficiency are still critical in most cases.

10.2. Future Work

The findings of this study open several avenues for future research, which could further enhance the integration of LCA into the early-stage design process:

- **Refinement of LCA Data:** One of the major limitations of this study is the reliance on generalized data for lifecycle emissions, particularly for construction and end-of-life phases. Future work should focus on developing more accurate databases and methodologies for estimating emissions in these phases, with special attention to regional differences in steel sourcing and recycling practices. Additionally, expanding the scope of the analysis by including previously overlooked emissions, such as crew-related emissions during operation, or other indirect emissions, would enhance the comprehensiveness of the lifecycle assessment.
- **Circular Economy and Recyclability:** While this study did not focus on circular economy principles, future research could explore how material reuse and recyclability could reduce lifecycle emissions. The role of recyclable materials and efficient end-of-life processes could contribute significantly to reducing emissions in construction and decommissioning phases.
- **Effect of Longer Lifetimes:** The impact of different vessel lifetimes on lifecycle emissions should be further investigated. Longer lifetimes may reduce the need for new constructions but increase maintenance and operational emissions. This trade-off could offer insights into optimal design decisions based on the expected lifetime of the vessel. This would include reusing or re-purposing the hull without cutting or rerolling, leading to reduced lifecycle emissions for a new vessel. Additionally, this case study should account for more regulatory impacts on the ship, ensuring that the generated designs comply with operational regulations throughout the considered lifetime.
- **Different Maintenance Strategies:** As maintenance is a significant source of emissions, future work could explore different maintenance strategies and their long-term impact on lifecycle emissions. This could include using more durable materials or innovative maintenance techniques that reduce emissions over time. More frequent or enhanced maintenance efforts could extend the vessel's lifetime, potentially reducing the need for new construction and lowering overall lifecycle emissions. Exploring this trade-off would provide valuable insights into the balance between maintenance emissions and the benefits of a longer operational lifespan.

A wide range of additional case studies would provide valuable insights into the effects of various design aspects on lifecycle emissions and their prioritization during the design process. For low-emission vessels, these case studies would be particularly useful in determining the trade-offs between operational and construction emissions, ensuring that the optimal design point is well-supported by data. This would be especially helpful for targeting the priorities for emission reduction, as the total emissions could vary significantly depending on the specific impacts of each case study. Trade-offs could be further investigated across all domains earlier investigated, being sourcing, construction, maintenance, end-of-life, and operation. By exploring these areas, future studies could identify when and to what extent specific lifecycle phases should be prioritized, enabling more informed decisions for reducing emissions while balancing environmental and economic goals.

10.3. Conclusion

This chapter has highlighted the importance of integrating Life Cycle Assessment (LCA) into the vessel design process, demonstrating that considering full lifecycle emissions—including construction, maintenance, and end-of-life—provides a more comprehensive environmental perspective. While operational emissions dominate for most vessels, the inclusion of non-operational emissions can shift design priorities, especially in low-emission scenarios. Uncertainties, such as those related to steel sourcing, underscore the need for refined data.

Suggestions for future work emphasize the development of more accurate LCA data, exploring circular economy approaches, assessing the impact of extended vessel lifetimes, and improving maintenance strategies. Full integration of LCA into the *Blended* Design tool will further support sustainable vessel design.

CII Including, effect on ROI when ships can not operate in the future anymore. So the ROI would shift maybe, as vessels with a not complying CII in the future are left out...

11

Conclusion

This research aimed to integrate full Life Cycle Assessments (LCA), encompassing construction, operation, and end-of-life phases, into the early-stage design of offshore vessels using the *Blended* Design tool. By expanding beyond the traditional focus on operational emissions, this study demonstrates a holistic approach to optimizing ship designs for both cost and environmental performance.

The results highlight that while operational emissions dominate a vessel's lifecycle emissions, construction and maintenance phases can significantly influence design decisions, particularly in low-emission operational scenarios. For HFO-fueled ships, however, reducing operational emissions remains the primary focus due to their overwhelming lifecycle contribution. This study also underscores the role of uncertainties in sourcing and construction. Although their impact is mitigated in typical scenarios, they become more significant in low-emission cases or with high regional variability, potentially affecting optimal design decisions.

Key Insights

- **Lifecycle Integration:** Expanding LCA to encompass non-operational phases ensures high-impact decisions in early design are informed by a comprehensive understanding of environmental and cost implications, from material extraction to end-of-life processes.
- **Blended Design Evolution:** Adapting *Blended* Design to integrate lifecycle considerations supports balanced trade-offs between operational efficiency, construction impacts, and decommissioning sustainability, enhancing its value as an analytical tool.
- **Economic and Environmental Synergy:** Lifecycle approaches demonstrate that sustainability and cost-efficiency are not mutually exclusive. Optimal designs can achieve lower emissions, meet regulatory compliance, and provide competitive advantages.

Strategic Implications

- **Standardization of LCA in Ship Design:** The proposed framework can serve as a model for establishing industry-wide standards, driving uniformity in lifecycle impact assessments and fostering innovation.
- **Future-Proofing Designs:** Addressing construction and decommissioning phases prepares designs for evolving regulatory landscapes and market demands, ensuring long-term competitiveness.

Recommendations for Future Research

- Expand the scope of LCA to include additional environmental impacts for a more comprehensive assessment.
- Explore the integration of circularity metrics alongside LCA within *Blended* Design to address long-term sustainability goals.
- Conduct case studies across other vessel types to refine methodologies and generalize findings for broader application.

Final Remark

This study demonstrates the clear added value of ensuring design decisions are informed by the full lifecycle impact of the vessel, spanning construction, operation, maintenance, and end-of-life phases. Such insights are particularly valuable in cases where operational emissions are relatively low or regional variability in material sourcing and construction processes plays a critical role. By highlighting the environmental footprint of non-operational phases, LCA has the potential to challenge traditional design priorities and uncover opportunities for innovation.

In certain scenarios, this approach can result in fundamentally different designs compared to conventional methods, with design parameters that diverge significantly from those based solely on operational emissions.

This integration empowers designers and stakeholders to meet increasingly stringent regulatory requirements while aligning with broader sustainability objectives, such as the IMO decarbonization targets, global climate goals, and voluntary initiatives, all while maintaining competitiveness. Furthermore, adopting LCA in early design stages reinforces a proactive, forward-looking approach to innovation, ensuring vessels are future-proofed against evolving market demands and environmental pressures.

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