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Felipe Santos Dutra

The adoption of alternative fuels in the maritime sector

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-Graduação em Engenharia de Produção of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Engenharia Produção.

Advisor: Prof. Antônio Márcio Tavares Thomé
Co-Advisor: Prof. Rodrigo Goyannes Gusmão Caiado

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To my father and mother, whose examples of
hard work and dedication have always inspired me.

To my wife, for her support throughout this
journey and new choice of life.

To my son, who motivates me to be a better
person and to strive for a better world for his
generation.

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Abstract

Dutra, Felipe Santos; Thomé, Antônio Márcio Tavares, Caiado, Rodrigo Goyannes Gusmão. **The adoption of alternative fuels in the maritime sector.** Rio de Janeiro, 2024. 170p. Dissertação de Mestrado - Departamento de Engenharia Industrial, Pontifícia Universidade Católica do Rio de Janeiro.

This dissertation, titled "The Adoption of Alternative Fuels in the Maritime Sector," critically examines the decision-making processes in the maritime industry under the lens of Institutional Theory and the Multi-Level Perspective (MLP) on sustainability transitions. Employing a mixed-method approach, which integrates a comprehensive literature review with a detailed survey, the study explores how institutional pressures and sustainability transitions influence the shift toward low-carbon fuels in maritime operations.

The research identifies key enablers such as technological innovations and economic incentives, and addresses barriers including high initial costs, infrastructural limitations, and regulatory challenges. It also highlights the significant influence of coercive, normative, and mimetic pressures in shaping organizational behaviours towards sustainable practices. A novel decision-making framework that synthesizes insights from Institutional Theory and MLP is proposed to facilitate the adoption of alternative fuels, supporting maritime companies in navigating the complexities of sustainability transitions. A research agenda is also put forward.

The practical relevance of this study lies in its strategic framework, which provides actionable insights for maritime companies pursuing environmental sustainability. Academically, the dissertation makes a significant theoretical contribution by applying and extending Institutional Theory and MLP within the context of maritime fuel transitions, enhancing our understanding of the interplay between institutional dynamics and sustainability practices in the maritime industry.

Keywords

Alternative Fuels, Maritime Industry, Institutional Theory, Multi-Level Perspective, Sustainability Transitions, Decision-making.

Resumo

Dutra, Felipe Santos; Thomé, Antônio Márcio Tavares, Caiado, Rodrigo Goyannes Gusmão. **A Adoção de Combustíveis Alternativos no Setor Marítimo.** Rio de Janeiro, 2024. 170p. Dissertação de Mestrado - Departamento de Engenharia Industrial, Pontifícia Universidade Católica do Rio de Janeiro.

Esta dissertação explora os processos de decisão que envolvem a transição para combustíveis de baixo carbono no setor marítimo, uma indústria vital para o comércio global, mas também uma significativa fonte de emissões de gases de efeito estufa. A investigação é guiada pela Teoria Institucional e pela Perspectiva Multinível (MLP) sobre transições para a sustentabilidade, oferecendo uma análise abrangente de como pressões institucionais e a necessidade de sustentabilidade influenciam as práticas organizacionais e as decisões estratégicas na adoção de novas tecnologias energéticas. Este estudo destaca-se por aplicar e ampliar teorias estabelecidas no contexto específico das transições de combustíveis no setor marítimo, contribuindo tanto para a teoria quanto para a prática ao fornecer um modelo de tomada de decisão aprimorado para o uso de combustíveis alternativos.

O estudo adota uma abordagem de métodos mistos, integrando uma revisão sistemática de literatura e uma pesquisa detalhada com stakeholders da indústria marítima. A revisão de literatura foca na identificação de lacunas existentes e na compreensão das dinâmicas institucionais e de mercado que impactam a adoção de tecnologias de baixo carbono. A pesquisa, por outro lado, coleta dados primários sobre as percepções, barreiras e facilitadores percebidos por profissionais do setor, utilizando tanto análises quantitativas quanto qualitativas para uma compreensão mais profunda das atitudes em relação à transição energética.

Os resultados revelam que inovações tecnológicas e incentivos econômicos emergem como facilitadores críticos, enquanto barreiras significativas incluem custos iniciais elevados, limitações de infraestrutura e desafios regulatórios complexos. Mais importante ainda, o estudo identifica e discute o papel das pressões institucionais - coercitivas, normativas e miméticas - e como elas moldam comportamentos organizacionais em direção a práticas sustentáveis. A dissertação propõe um *framework* de tomada de decisão que integra essas pressões com considerações práticas, ajudando as empresas a alinhar suas estratégias operacionais com objetivos de sustentabilidade ambiental.

O trabalho expande a aplicação da Teoria Institucional e MLP ao examinar como essas teorias podem ser inter-relacionadas e aplicadas para explicar a complexidade das transições para combustíveis mais limpos na indústria marítima. A pesquisa oferece às empresas marítimas um modelo estratégico para orientar a transição para combustíveis alternativos, enfatizando a importância de um ambiente regulatório de suporte, cooperação internacional e colaboração entre *stakeholders* para facilitar essa mudança.

O estudo conclui que a transição para combustíveis alternativos no setor marítimo é profundamente influenciada por uma complexa interação de fatores tecnológicos, econômicos e institucionais. O *framework* de tomada de decisão proposto ajuda as empresas marítimas a compreender essas dinâmicas existentes e também tráz à tona o papel crucial da inovação tecnológica, avaliações de impacto abrangentes e o desenvolvimento de políticas e *frameworks* regulatórios eficazes. Por fim, a dissertação sugere uma agenda de pesquisa futura focada na análise de transições tecnológicas específicas e na evolução dos comportamentos institucionais em resposta a desafios ambientais globais.

Palavras-chave

Combustíveis Alternativos, Teoria Institucional, Perspectiva Multinível, Transições para a Sustentabilidade, Tomada de Decisão, Navegação Sustentável.

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Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits - not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities. But technology and social organization can be both managed and improved to make way for a new era of economic growth.

Brundtland Report (1987, p.15)

*What do **YOU** care what other people think?*

Arlene Feynman, in, love letters to Mr. Richard P. Feynman.

1 Introduction

The transportation sector is highly energy-intensive, accounting for approximately 26% of global energy consumption (IEA, 2023). It encompasses various modes such as aviation, railways, and navigation. Among these, maritime transportation is the most efficient in terms of goods transported per Greenhouse Gas (GHG) emission (IMO, 2021), owing to their capacity to carry large volumes and the use of internal combustion engines. Navigation, playing a crucial role in global logistics and the economy, transports approximately 90% of the world's traded goods (UNCTAD, 2020).

Despite maritime transportation's energy efficiency, 99% of vessels use internal combustion engines and fossil fuel for propulsion. GHG emissions from maritime transportation in 2018 accounted for about 2.89% of global anthropogenic emissions and could represent between 90% and 130% of 2008 emissions by 2050 (IMO, 2021). According to the Intergovernmental Panel on Climate Change (IPCC) report, global warming emerges as a problem of great relevance, requiring immediate action from society (IPCC, 2023).

In recent years, maritime companies have faced increasing pressures stemming from many sources, ranging from regulatory mandates (Bloor et al., 2013; Helfre & Boot, 2013; Joung et al., 2020), to societal expectations (Dare et al., 2014; Smits et al., 2016; Voyer & van Leeuwen, 2019) and market demands (Agnolucci et al., 2014; Lagouvardou et al., 2020). Institutional theory profoundly influences these pressures, posing that organizations are embedded within broader institutional environments characterized by norms, rules, and regulations that shape their behaviour and decision-making processes (Oliver, 1991). Understanding these institutional pressures is crucial for analysing their impact on the maritime industry's operational efficiency, sustainability, and economic outcomes. A companion theory complementing the Institutional theory is the Multi-Level Perspective (MLP) of sustainability transitions in transportation (Ferrer & Thomé, 2023). MLP provides global models focusing on niches (the locus for radical innovations), regimes (the dominant practices and rules), and landscapes (the broader contextual factors) (Geels, 2019).

One of the primary institutional pressures maritime companies face is regulatory scrutiny and compliance. With growing awareness of environmental issues and climate change, regulatory bodies worldwide have implemented stricter emissions standards and sustainability regulations for the maritime sector. Compliance with these regulations entails financial investments in retrofitting vessels or adopting cleaner technologies and necessitates changes in operational practices and fuel choices (Sun et al., 2023). Failure to comply with regulatory requirements can result in penalties (U.S. Department of Justice, 2015) and reputational damage (McGuire et al., 2022), highlighting the importance of institutional pressures in driving operational efficiency and sustainability within the industry (Ampah et al., 2021).

Moreover, societal pressures play a significant role in shaping the behaviour of maritime companies. Stakeholders, including customers, investors, NGOs, and the general public, increasingly expect businesses to operate in an environmentally responsible manner and contribute positively to social welfare. As such, maritime companies face mounting pressure to demonstrate their commitment to sustainability by reducing emissions, minimizing waste generation, and investing in renewable energy sources (Yuen et al., 2017). Failure to address societal expectations can lead to consumer boycotts (Afego & Alagidede, 2021), investor divestment (Balzac, 2016; Nyuur et al., 2017), and diminished brand reputation (Dixon et al., 2016), underscoring the interconnectedness between institutional pressures, sustainability efforts, and economic outcomes.

Furthermore, market forces exert a substantial influence on the behaviour of maritime companies. As global supply chains become increasingly complex and interconnected, customers are placing greater emphasis on sustainability and environmental stewardship when selecting transportation partners (Poulsen et al., 2016). Consequently, maritime companies prioritising sustainability and efficiency in their operations are better positioned to attract and retain customers, enhance their competitive advantage, and achieve long-term profitability (Raza & Woxenius, 2023; Yuen et al., 2019). This illustrates the symbiotic relationship between institutional pressures, operational efficiency, sustainability practices, and economic performance within the maritime industry.

The adoption of alternative fuels in the maritime industry is heavily influenced by a multifaceted set of decision-making criteria that ensure compatibility with both existing operational frameworks and future sustainability targets. Spoof-Tuomi & Niemi (2020) emphasize the importance of economic feasibility and environmental impact as primary drivers in fuel selection. These authors argue that alternative fuels' viability is assessed through direct cost implications and their potential to reduce greenhouse gas emissions in compliance with international standards. Bayraktar & Yuksel (2023), Bui et al. (2021) and Ma et al. (2021) highlight the critical role of regulatory compliance and technological readiness, suggesting that the successful integration of new fuels depends significantly on the current infrastructure and technological advancements. Additionally, operational characteristics such as fuel efficiency and adaptability to existing vessel engines are also pivotal, as they directly affect the practical implementation and performance outcomes of adopting new fuel technologies (Karvounis et al., 2022; Sherbaz & Duan, 2012). These criteria collectively guide stakeholders in making informed decisions that balance operational efficiency, environmental responsibility, and economic practicality.

In transitioning towards low-carbon fuels in the maritime industry, several barriers and enabling factors have been identified across various academic studies, highlighting this shift's complexity and multi-faceted nature. The primary obstacles identified across various studies include economic factors such as high initial investment costs and operational expenditures (Gren et al., 2020; Tran & Lam, 2022), technological challenges (Temiz & Dincer, 2021; Z. L. Yang et al., 2023) and safety concerns (Inal et al., 2022; H. Wang et al., 2023), and infrastructural deficiencies, such as the lack of refuelling and bunkering facilities (Besbes & Savin, 2009; Kim et al., 2021). Additionally, regulatory uncertainties often complicate compliance and long-term planning for ship operators (Irena et al., 2021; Mäkitie et al., 2022). These barriers are further compounded by supply chain complexities, which affect the availability and consistent delivery of alternative fuels (Hussein & Song, 2021; Khatri & Srivastava, 2016). Consequently, overcoming these multidimensional challenges requires a concerted effort from all industry stakeholders, including regulatory bodies, technology providers, and maritime companies.

Regulatory support and the environment drive the adoption of sustainable practices through clear regulatory frameworks and heightened public consciousness about environmental impacts (Alamoush et al., 2022; Rivarolo et al., 2021). Technological advancements and ongoing research and development also play crucial roles by enhancing the efficiency and feasibility of alternative fuels, addressing the existing technical and economic barriers (Kanchiralla et al., 2022; Rivarolo et al., 2021). Additionally, economic incentives such as subsidies and cost savings are vital for overcoming the financial challenges of implementing new technologies (Alamoush et al., 2022; Foretich et al., 2021). Collaborative efforts among industry stakeholders, including shipping companies, technology providers, and regulatory bodies, are essential for fostering innovation and aligning efforts towards sustainability goals (Alamoush et al., 2022; Lee et al., 2020). These factors create a conducive environment for the maritime industry to transition towards more sustainable fuel options, aligning with global efforts to reduce greenhouse gas emissions and enhance environmental stewardship.

In assessing alternative fuels for the maritime industry, various decision-making models have been employed to address the multifaceted challenges of transitioning to low-carbon solutions. Life Cycle Assessment (LCA) is widely utilized to evaluate the environmental impacts across the entire life cycle of different fuels, providing a comprehensive understanding of their sustainability profiles (Ballester et al., 2020; Spoof-Tuomi & Niemi, 2020). Economic analyses further complement these assessments by examining the cost implications of adopting such fuels, considering factors like fuel prices, operational costs, and potential savings (Spoof-Tuomi & Niemi, 2020). Marginal Abatement Cost Curves (MACCs) offer a strategic approach by identifying cost-effective options for emission reduction, facilitating prioritization based on economic viability (Irena et al., 2021). Scenario planning and carbon pricing models are also integral, helping stakeholders visualize future scenarios and internalize the cost of carbon emissions, thus steering decision-making towards environmentally and economically viable solutions (Ballester et al., 2020; Liu et al., 2020; Spoof-Tuomi & Niemi, 2020).

In addition to these models, on the one hand, Multi-Criteria Decision-Making (MCDM) approaches have been adopted to further refine the selection process of alternative fuels in the maritime industry. MCDM techniques, such as the Analytic Hierarchy Process (AHP) (Saaty, 2008) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have been instrumental in systematically evaluating and ranking fuel alternatives against a set of prioritized criteria. For instance, Atak et al. (2023) utilized the fuzzy AHP TOPSIS method to assess various engine options for merchant vessels, emphasizing environmental impacts, safety, economic feasibility, and onboard applicability. The AHP is extensively employed to weigh various criteria—including environmental impact, cost, and technological readiness—against each other, enabling stakeholders to assess and prioritize fuel alternatives based on multiple performance metrics (Z. Liu et al., 2020). Optimization models, on the other hand, leverage mathematical and computational methods to find the most efficient solutions for fuel selection, focusing on minimizing costs while maximizing environmental and operational benefits (Paulauskas et al., 2018; Yang et al., 2020). These models often incorporate constraints and parameters specific to maritime operations, such as fuel availability, regulatory compliance, and scalability of fuel technologies.

The motivation for this study is fuelled by the imperative of sustainability. Historically dependent on fossil fuels, the maritime industry is under increasing scrutiny and regulatory pressure to reduce emissions and adopt more eco-friendly practices (Ampah et al., 2021; Joung et al., 2020). This motivation arises from the need to comply with stringent regulations set by the International Maritime Organization (IMO) and the understanding that sustainability is crucial for the sector's long-term viability. The MLP provides a framework for understanding better the sustainability transition embedded in the innovation and adoption of alternative fuels in the Maritime Industry, depicting niches, dominant regimes of conventional technologies and business models and the pressures exerted by the landscape (Ferrer & Thomé, 2023).

However, the motivation for this project goes beyond regulatory compliance. There is also the additional motivation to understand the decision-making process for adopting alternative fuels in maritime operations. As the industry seeks to transition from fossil fuels to sustainable alternatives, crucial questions arise about economic viability (Korberg et al., 2021), operational efficiency (Acciaro & Wilmsmeier, 2015; Agnolucci et al., 2014), sustainability (Acciaro, 2014; Corbett & Fischbeck, 1997; Zis, 2019), and company competitiveness (Midoro et al., 2005; Oliver, 1997). Understanding how this transition will affect daily operations, operational costs, and profitability is essential for strategic planning.

This dissertation addresses a globally significant problem: reducing GHG emissions and transitioning to more sustainable fuels in the maritime industry. Its relevance transcends academic boundaries since maritime industry emissions directly affect climate change and global GHG reduction targets established by the international community. Therefore, the research contributes to a planet-wide objective: mitigating climate change (United Nations Environment Programme, 2015).

This dissertation's opportunity is unequivocal and embedded in a dynamic and challenging context. A constantly evolving scenario in the maritime industry is observed, where various alternative fuels are being tested and gradually introduced into operations (Rosenberg & Leitão, 2023). In response to the pressing need for climate change action and in support of United Nations Sustainable Development Goal 13 - "Take urgent action to combat climate change and its impacts", the IMO revised its ambitions in 2023, shaping the 2023 IMO GHG Strategy. This revision emphasizes four key directives: (i) Carbon Intensity Improvement aiming for the carbon intensity of new ships to decline through further improvement of energy efficiency and review of design requirements for ships to strengthen energy efficiency; (ii) Reduction in CO2 Emissions, targeting a reduction of at least 40% in CO2 emissions per transport work by 2030, compared to 2008 levels; (iii) Uptake of Zero or Near-Zero GHG Emission Technologies, increasing the uptake of zero or near-zero GHG emission technologies, fuels, and energy sources to represent at least 5%, striving for 10% of the energy used by international shipping by 2030 and; (iv) Net-Zero GHG Emissions, peaking GHG emissions from international shipping as soon as possible and aiming to reach net-zero GHG emissions by or around 2050, considering different national circumstances. These imperatives are part of the global landscape of sustainability transitions in transportation predicted under MLP (Geels, 2019), and have driven research and development (R&D) of various sustainable fuel options.

This diversity of alternatives, including hydrogen-based fuels, ammonia, Liquefied Natural Gas (LNG), ethanol, methanol, and biofuels, represents a fundamental transformation opportunity in the industry (Cabrera-Jiménez et al., 2022; Chatterton, 2021; Lammons et al., 2015; Lewis, 2018; Reinsch & O'Neil, 2021; Sahnen, 2019; H. Wang et al., 2023; Youngs, 2010) While there is a wealth of options, the future landscape remains open, with uncertainties regarding these new fuels' availability, costs, infrastructure, and environmental impact.

The dissertation addresses the pressing need for decarbonizing maritime transportation by examining key research themes, evaluating the current state of R&D in sustainable fuels, identifying enablers and barriers to their adoption, and exploring decision analysis methods in fuel selection.

Thus, the proposed research benefits from the opportunity to evaluate and understand the full spectrum of sustainable fuel alternatives in a time of profound change. It fits into an environment of experimentation and adaptation, where maritime companies face crucial challenges and decisions that can shape the industry's future. In response to these challenges, this dissertation poses a major research question:

RQ1- How does the application of decision analysis contribute to the sustainable fuel selection processes within the maritime industry?

To further explore this inquiry, secondary research questions are formulated to explore key themes in sustainability within the maritime sector:

RQ 2 - What are the main research streams of sustainability for the shipping industry? How has it evolved?

RQ 3 - What are the barriers to and enablers of the adoption of sustainable fuels? These questions are strategically designed to align with this research endeavour's overarching aim and objectives.

Through a combination of quantitative and qualitative investigation (Creswell, 2010), the research's general objective is to analyse trends, the role of decision analysis, barriers and enablers in advancing sustainable fuel choices within the maritime industry, ultimately contributing to efforts to mitigate climate change, aiding in formulating informed strategies for reducing greenhouse gas emissions and promoting environmental sustainability in maritime transportation.

The specific objectives are as follows: Firstly, to map the main research themes in sustainability in the maritime industry, employing both qualitative and quantitative methodologies. This objective involves identifying and quantifying the primary areas of research in sustainability within the industry and analysing the longitudinal evolution of these research streams through a systematic literature review. The content analysis will lead to a qualitative appraisal of how these research areas have developed over time and the key advances achieved within them.

The second specific objective is to evaluate the current state of R&D in the Maritime Industry regarding alternative and sustainable fuels. This objective encompasses a comprehensive quantitative analysis of the current R&D landscape in the maritime industry regarding alternative and sustainable fuels, quantifying trends and areas of focus. Furthermore, it involves administering a survey questionnaire to the Brazilian maritime industry on sustainable purchases to understand the main drivers for the adoption of sustainable purchase practices and the services and supplies that are more relevant to sustainable outcomes in maritime operations.

The third specific objective aims to identify and analyse the enablers and barriers to the adoption of sustainable fuels in maritime transportation. This objective involves both quantitative and qualitative approaches. Quantitatively, it aims to collect and quantify the most frequently applied criteria for evaluating the sustainability of alternative fuels in the maritime industry. Qualitatively, it analyses how these criteria have adapted to regulatory changes and new environmental concerns.

This study focuses on examining various aspects related to the decarbonization of maritime transportation, with a specific scope emphasising sustainable fuel alternatives. The research encompasses multiple objectives, contributing to both theory and practice by mapping research themes in sustainability within the maritime industry, evaluating the current state of R&D in sustainable fuels, identifying enablers and barriers to their adoption, and exploring decision analysis methods in fuel selection. The study's scope extends to quantitative and qualitative analyses, drawing insights from data collected through surveys, literature reviews, and expert interviews. By addressing these objectives, the study aims to contribute valuable insights to the ongoing discourse on sustainable practices in the maritime industry. It offers four main contributions: a classification of alternative fuels and the enablers and barriers to their adoption, two frameworks based on the Institutional Theory, a research agenda and a meta-theory by combining the Institutional Theory with MLP in sustainability transitions.

Despite its comprehensive approach, this study is subject to several limitations. Firstly, the study relies on the available academic and grey literature based on the Scopus and Web of Sciences databases, which may introduce biases or gaps in the analysis. Additionally, the choice of keywords to search the databases might artificially restrict the results. Furthermore, the dynamic nature of the maritime industry and regulatory landscape poses challenges in capturing real-time developments and trends. Another limitation pertains to the complexity of decision-making processes within maritime companies, which may not be fully captured through quantitative analysis alone, despite the sequential mixed-method approach used in this dissertation. Finally, while efforts are made to ensure the validity and reliability of the research findings, inherent limitations in data collection methods and sample representativeness may impact the conclusions' robustness. Despite these limitations, the study endeavours to provide valuable insights into sustainable fuel adoption in maritime transportation, paving the way for future research and policy interventions in this critical area.

The dissertation is structured as follows. After this introductory, chapter 2 that sets the stage by delineating the theoretical background, subdivided into sections 2.1 - Ontological positioning, section 2.2 - The Foundation of Institutional Theory, section 2.3 - Multi-Level Perspective on Transition to low-carbon Fuels, and, finally section 2.4 - The use of theories in systematic literature reviews. Building upon this foundation, Chapter three outlines the methodological framework adopted in the study, detailing the research design, data collection methods, analysis procedures, and ethical considerations. Chapter four presents the results of the analysis undertaken in this dissertation and reports in section 4.1 the results of the scoping review, showing the main elements of the decision-making process of adopting alternative fuels and in section 4.2 the results of the survey about sustainable purchasing practices undertaken in the Brazilian maritime industry. Utilizing both quantitative and qualitative approaches, this chapter presents the results of the systematic literature review of how the key sustainability themes in the maritime industry have evolved, a decision-making framework for alternative fuels adoption and the results of the management practices and drivers for sustainability within the maritime sector in Brazil.

Chapter five discusses the results in light of the theory and the literature reviewed, synthesizing the findings from the preceding chapters and organizing them into a cohesive framework. This chapter provides a comprehensive discussion that integrates quantitative data and qualitative insights, culminating in a meta-theory derived from the institutional theory and the multi-level perspective (MLP) on transitions toward sustainability in the maritime sector. This meta-theory offers a robust foundation for understanding the adoption of alternative fuels in the maritime industry.

Finally, chapter six concludes the dissertation by summarizing the key findings, addressing the research questions and objectives, discussing implications for industry and policy, and offering recommendations for future research directions. The dissertation structure ensures a logical progression of ideas, from theoretical exploration to empirical analysis, culminating in actionable insights to advance sustainable practices within the maritime transportation sector.

2 Theoretical Background

The theoretical foundation of this thesis is pivotal in understanding the complex and multifaceted nature of the transition to sustainable maritime fuels. This chapter explores the essential theories and paradigms that form the backbone of this research, providing a structured and comprehensive framework for analysing the adoption of low-carbon fuels in the maritime industry. By integrating diverse theoretical perspectives, this chapter aims to elucidate the intricate dynamics that influence organizational behaviour and decision-making processes within the context of sustainability transitions.

Section 2.1 explores the ontological positioning that underpins this research. It discusses the role of ontologies in operations management and sustainability research, highlighting how structured frameworks facilitate communication, data integration, and complex decision-making. The importance of establishing a clear research paradigm is emphasized, detailing the philosophical assumptions, beliefs, and principles that guide the research process.

In Section 2.2, the foundation of institutional theory is examined. This section reviews the evolution of institutional theory, focusing on how institutions influence organizational behaviour and decision-making. It discusses the various approaches to institutionalization and the impact of external pressures, such as coercive, mimetic, and normative isomorphism, on organizations. The relationship between institutional theory and corporate social responsibility is also explored, highlighting how institutional conditions shape corporate behaviour.

Section 2.3 provides an overview of the multi-level perspective (MLP) on transitions to low-carbon fuels. The MLP framework is used to analyse the dynamics of large-scale socio-technical transformations required for sustainability. This section discusses the interactions between niches, regimes, and landscapes, emphasizing the role of innovation, policy, markets, and cultural changes in driving sustainability transitions.

Finally, Section 2.4 discusses the use of theories in systematic literature reviews. It outlines the contribution of theoretical frameworks to literature reviews, emphasizing their role in synthesizing diverse perspectives and findings from various studies.

2.1 Ontological positioning

Ontologies in operations management offer structured frameworks for standardized and organized information, facilitating communication, data integration and supporting complex decision-making scenarios (Chandrasekaran et al., 1999; Grubic & Fan, 2010). In sustainability research, the structured frameworks define and categorize concepts, entities, and relationships within the sustainability domain, organising knowledge, communications, data integration, and complex analyses and decision-making processes, covering environmental impacts, social equity, economic viability, and governance structures. To quote a few examples, one can look at the use of ontologies for environmental impact analysis, UN Sustainable Development Goals (SDG), and circular economy (Chou, 2021). Ontologies are embedded in the larger realm of research paradigms (Creswell & Poth, 2017).

Setting a research paradigm is important in the research field, as it serves as the foundational framework that guides the researcher's approach, methodology, and interpretation of findings (Glasgow, 2013; Kaushik & Walsh, 2019). A research paradigm encompasses the philosophical assumptions, beliefs, and principles that underpin the study, shaping the researcher's worldview and influencing every aspect of the research process (Denscombe, 2008). Research paradigms comprise ontology (the nature of reality and what can be known about it), epistemology (the nature of knowledge and how it can be acquired), methodology (the overall approach to research, including the methods and techniques used for data collection and analysis), and axiology (the role of values and ethics in the research process) (Creswell & Poth, 2017).

By establishing a clear research paradigm, researchers can define the boundaries of their investigation, determine the appropriate methods for data collection and analysis, and align their study with established theoretical frameworks (Kahlke, 2014). A well-defined research paradigm provides coherence and consistency to the research endeavour, ensuring that the study remains focused, rigorous, and methodologically sound (Mitchell, 2018). The choice of a research paradigm not only shapes the research design but also influences the validity, reliability, and relevance of the study's outcomes, highlighting the critical role of paradigm selection in shaping the trajectory and impact of academic research (Frey, 2022).

There can be several research paradigms applied to research design (Creswell et al., 2007; Frey, 2022). Positivism is a philosophical approach that emphasizes the importance of objective measurements and rational analysis (Frey, 2022). It asserts that true knowledge comes from clear, quantifiable observations of behaviours, actions, or responses. According to positivism, only phenomena that can be measured in this manner can be truly understood or confirmed (Straub & Gefen, 2004). It promotes the idea that scientific insights arise from the systematic collection of neutral, unbiased data through direct observation (Ryan, 2018). Thus, phenomena that cannot be directly observed and quantified are considered irrelevant or insignificant. Positivism generally favours quantitative data collection methods. Another research paradigm, Interpretivism, posits that reality is subjective, varied, and constructed by social interactions (Ryan, 2018). This viewpoint suggests that understanding an individual's reality can only be achieved through their own experiences, which are influenced by their unique historical and social contexts (Walsham, 1995). Interpretivist methods focus on in-depth inquiry and observation to uncover or develop a comprehensive understanding of the subject being studied (Moon & Blackman, 2014; Schwandt, 1998). This approach is typically aligned with qualitative data collection techniques.

In addition to these two research paradigms, there is pragmatism, a philosophical approach that emphasizes experimentation, action, and problem-solving (Surie & Ashley, 2008) within an actual real-world situation (Glasgow, 2013; Kaushik & Walsh, 2019). This research paradigm is soused in this dissertation. Pragmatism is characterized by a focus on gaining the understanding necessary to deal with problems as they arise, rather than uncovering antecedent real truths. In a pragmatic approach to qualitative research, the focus is on the practical consequences and utility of knowledge in real-world contexts (Goldkuhl, 2012).

Pragmatism values the application of knowledge to addressing practical issues and making a difference in the world. Researchers adopting a pragmatic stance prioritize the usefulness of their findings and aim to generate knowledge that can inform decision-making and lead to tangible outcomes (Kelly & Cordeiro, 2020). By integrating qualitative and quantitative methods, pragmatist research seeks to provide actionable insights that bridge the gap between theory and practice, ultimately contributing to practical solutions and advancements in various fields

(Glasgow, 2013; Mitchell, 2018). Pragmatism is instrumental in research on organizational processes as it enables researchers to map the consequences or meanings of social action for different individuals within an organization, addressing weaknesses in existing organizational research (Kelly & Cordeiro, 2020).

The strength of pragmatic investigations lies in their flexibility and utility. They are straightforward to describe and report, making them particularly advantageous when unexpected results arise from prior studies (Goldkuhl, 2012). Pragmatic ontologies facilitate the generalization of data, aid in designing and validating instruments, and enable researchers to develop holistic analyses that incorporate numerous relevant factors into the study (Morgan, 2014; Surie & Ashley, 2008). However, like any other research paradigm, pragmatism has its limitations. The preparation and execution of studies can be time-consuming compared to more traditional paradigms (Goldkuhl, 2012). Additionally, integrating different types of data can lead to discrepancies that are challenging to interpret (Surie & Ashley, 2008). In sequential designs, deciding the order of data collection and determining the appropriate timing to proceed with studying different groups over extended periods can also be difficult (Creswell & Plano Clark, 2017).

Popa et al. (2015) state that mainstream scientific methodologies encounter several significant challenges when tackling sustainability issues. Firstly, sustainability problems are marked by the involvement of multiple decision-makers, each holding diverse values and perspectives (Alhaddi, 2015; Martins & Pato, 2019; Videira et al., 2012). This variety complicates the process of achieving a consensus on solutions, as different stakeholders often have conflicting views on how to address these issues. Secondly, these problems are rife with pervasive uncertainties due to changing environmental conditions, societal impacts, and unpredictable future outcomes. Additionally, sustainability concerns often entail spatial and intertemporal externalities that extend across various scales and timeframes, complicating the assessment and management of their full impacts (Gilbert et al., 2018a; IMO, 2024c; Luttenberger & Luttenberger, 2017; Mondello et al., 2023). Another dimension to consider is the evolution of policy objectives, which continually adapt in response to new societal demands, environmental shifts, and advancements in scientific understanding. Lastly, the concept of reflexivity is often overlooked in mainstream methodologies. Reflexivity involves critically examining the values, assumptions, and orientations that underpin sustainability research. Methodologies must, therefore, be flexible and responsive to accommodate these changes. Without such scrutiny, building social legitimacy for sustainability solutions becomes significantly more challenging (Popa et al., 2015).

To overcome these challenges, there is a clear need for a shift towards transdisciplinary collaborations (Popa et al., 2015). Such collaborations should not only integrate scientific and extra-scientific expertise but also promote reflexivity and strive to make meaningful contributions to both societal and scientific advancement (Goldkuhl, 2012). This approach will enhance the capacity to address the multifaceted nature of sustainability issues effectively.

Pragmatism is particularly well-suited as the philosophical conception for this research into the decarbonization of maritime transportation, due to its focus on practical outcomes and real-world applications (Goldkuhl, 2012; Surie & Ashley, 2008). This philosophical stance aligns with the aim of the dissertation to not only understand but also actively contribute to the development of sustainable fuel adoption strategies in the maritime industry. Pragmatism can effectively address the unique challenges faced by this sustainability research in the maritime industry for six main reasons.

Firstly, it fosters mutual learning and co-production of knowledge, as pragmatism emphasizes collaborative learning and the co-production of knowledge (Popa et al., 2015), crucial in the context of sustainability where diverse stakeholders (Ashrafi et al., 2020; Videira et al., 2012) —ranging from industry experts to policymakers—must work together to innovate and experiment.

Second, it values critical awareness and action, by advocating for a critical examination of values, assumptions, and power and pressure structures, pragmatism aligns with the need for reflexivity in sustainability research (Glasgow, 2013). It supports the recognition and normative commitments, enhancing the ethical depth of research into sustainable maritime fuels (Cajaiba-Santana et al., 2020; Kuo et al., 2022).

Third, it favours social experimentation and learning processes, as pragmatism underscores the importance of learning through social experimentation (Goldkuhl, 2012), which is integral to addressing the practical challenges of adopting new fuels (DNV, 2021).

Fourth, it aids in testing theoretical models and frameworks in actual industry scenarios, such as through the application of decision analysis methods in fuel selection. Pragmatism allows for the adaptation of strategies based on their performance and effectiveness in real-world trials (Popa et al., 2015);

Five, the transformational dimension of pragmatism is about driving transformative change through reasoned, collective decisions on normative goals (Goldkuhl, 2012). In the context of this dissertation, involves pushing for systemic changes within the maritime industry by developing and advocating for strategies that not only mitigate environmental impacts but also are economically and technically feasible (Korberg et al., 2021; Tan et al., 2021; Temiz & Dincer, 2021);

Sixth, pragmatism enhances the process of collaborative deliberation (Glasgow, 2013), vital for sustainability where diverse and sometimes conflicting viewpoints must be harmonized. By promoting consensus-building and open dialogue, pragmatism ensures that the decision-making process in selecting and implementing sustainable fuels is inclusive, balancing various stakeholder interests and values (Ashrafi et al., 2020; Morris, 2020).

Incorporating pragmatism into the philosophical foundations of this dissertation justifies the use of a mixed-methods approach, enhancing the research’s relevance and applicability (Creswell & Plano Clark, 2017). By applying pragmatism, the research not only aims to understand the complex dynamics of sustainable fuel adoption in maritime transportation but also actively contributes to shaping practical, impactful solutions (Morgan, 2014). This holistic and action-oriented approach is essential for effectively tackling the maritime sector’s intricate and pressing sustainability challenges.

2.2 The Foundation of Institutional Theory

The concepts of institution and institutionalization have been defined in diverse ways, with substantial variation among approaches (Scott, 1987). According to Scott (1987), institutional theory provides a lens to understand the broader social context in which organizations operate and how institutions influence organizational behaviour and decision-making. The author defined the “many faces of the Institutional Theory”, reviewing the earliest and most influential works of Selznick (1948, 1957), from the end of the 1940s decade to the ‘50s, to other theorists such as Berger & Luckmann (1967) during the 1960s decade, and theorists such as Zucker (1987), Meyer & Rowan (1977), Berger et al. (1973), Tolbert & Zucker (1983), DiMaggio & Powell (1983).

Scott (1987) has defined four main approaches to the concept of institution and institutionalization within the Institutional theory realm. Selznick (1957) conceived institutionalization as a process of instilling value, viewing organizations not only as production or economic units and outcomes but also with a "natural dimension." This suggests that organizations also play a crucial role in shaping social and cultural contexts by promoting and internalizing specific values within their members and through their operations.

In a later work from Berger & Luckmann (1966) Institutionalization is creating reality and arguing about the nature and origin of social order. The authors argue that social order is a human construction created by human activity and interaction. This general conception was the foundation of the works of Meyer & Rowan (1977) and Zucker (1987), who emphasized that organizational forms can also be attributed to the existence of "rational myths" or shared belief systems. This new emphasis sheds light on the cultural elements of the organization, including symbols, cognitive systems, normative beliefs, and their respective sources. Additionally, it has changed the perception that organizations do not necessarily conform to a set of institutionalized beliefs merely because these constitute reality. Rather, they often do so because they are rewarded for it through increased legitimacy, resources, and competitiveness (Oliver, 1991).

This new view of institutionalization paved the way for DiMaggio & Powell (1983) to investigate the various processes that might cause an organization to adapt its structure to conform to an institutional pattern and become isomorphic. Meyer & Rowan (1977) theorized about the rationalized institutional structure, underscoring the multiplicity and diversity of institutional sources and beliefs – public opinion, educational systems, laws, courts, professions, regulatory structures, awards and prizes, certification and accreditation bodies, government endorsements and requirements. Such insights have led DiMaggio & Powell (1983) to classify such institutional patterns into a coercive, memetic and normative process that leads to conformity. This concept of institutional theory highlights how institutional rules influence the development and functioning of formal organizational structures.

Institutional isomorphism contributes to our understanding of collective rationality in organizational fields by highlighting how rational actors make decisions that lead to organizational similarity (Scott, 1987). DiMaggio & Powell (1983) argue that as organizations respond to external pressures and norms, they become more similar in structure and behaviour, even though individual actors may act rationally within their specific contexts. This process of isomorphism, driven by coercive, mimetic, and normative forces, results in a paradox where rational actors unintentionally make their organizations more alike as they try to differentiate them as a competitive advantage.

Campbell (2007) work presents an institutional theory that explores why corporations may choose to behave in socially responsible ways. The theory highlights the importance of various institutional conditions in shaping corporate behaviour, such as regulation, monitoring organizations, norms, associative behaviour, and stakeholder dialogues. According to the author, organizations have changed their behaviour for (i) adoption of socially responsible practices, (ii) compliance with regulations, (iii) stakeholder engagement, (iv) transparency and reporting, (v) corporate governance practices, (vi) cultural shift towards social responsibility and (vii) collaboration and partnerships. These changes in organizational behaviours reflect the evolving landscape of corporate social responsibility and the increasing recognition of the importance of ethical, sustainable, and socially responsible practices in modern business operations.

The relationship between institutional theory and Corporate Social Responsibility (CSR) was also the scope of the work of Brammer & Walker (2011). The authors emphasize the global diffusion of CSR practices and how organizations adopt and adapt them as they traverse different institutional environments. They also highlight the diversity of CSR practices across different regions and countries, including formal institutions such as laws and business associations and informal institutions like religious norms and tribal traditions, which influence corporate behaviour and social responsibility initiatives.

The moderating effects of institutional pressures on emergent green supply chain practices and performance were studied by Sarkis et al. (2011). Their research sheds light on the examples of institutional pressures that can impact green supply chain practices and how emergent green supply chain practices contribute to overall performance in the manufacturing industry. The authors highlight the relevance and applicability of Institutional Theory to businesses by emphasizing that firms adopt initiatives to gain legitimacy within society, navigate environmental challenges, improve their performance, and establish a positive reputation in the industry.

Approaching the organizational culture, Liu et al. (2010) explore the role of institutional pressures in the firm's intention to adopt internet-enabled supply chain management systems (eSCM). The authors point out some key ways in which organizational culture influences the implementation of these systems through (i) decision-making processes, (ii) resistance to change, (iii) communications and collaboration, (iv) learning orientation, and (v) adoption of best practices. A decision-making process that values innovation, collaboration, and risk-taking is more likely to support adopting new technologies. The resistance to change, rigid or hierarchical, may pose challenges to adopting new technologies, on the one hand. Openness to change and a flexible and adaptive culture are more likely to embrace and successfully implement SCM systems. On the other hand, a culture of open communication and collaboration, with knowledge sharing and collaboration across departments and hierarchical levels, fosters successful implementation. A continuous learning orientation, experimentation and improvement are more likely to support implementation. Finally, adopting best practices, valuing excellence, efficiency, and continuous improvement may prioritize adopting cutting-edge technologies like eSCM systems to stay competitive and drive operational excellence.

External pressures for institutional change are key to understanding the decarbonization initiatives in the maritime sector. DiMaggio & Powell (1983) classify institutional external pressures for change as coercive, mimetic, and normative.

The coercive isomorphism is a mechanism of institutional change driven by external pressures and the quest for legitimacy (DiMaggio & Powell, 1983). Organizations often conform to governmental regulations, societal expectations, or demands from other organizations to maintain their standing and credibility (Bansal, 2005; Meyer & Rowan, 1977; Zucker, 1987). This form of isomorphism manifests through direct responses to mandates, such as adopting new technologies for environmental compliance or implementing affirmative action policies to address discrimination allegations (Cajaiba-Santana et al., 2020; Kuo et al., 2022) Coercive forces exerted on organizations can range from formal regulations to informal cultural norms, shaping organizational behaviour and structure in response to external influences.

Bansal (2005) highlights the role of coercive pressures, such as regulations and media attention, in shaping organizational development towards sustainable practices. In the context of sustainable development, coercive pressures can arise from environmental regulations, public scrutiny, and negative media coverage. Regulations enforcing sustainable development and media attention significantly influence firms to commit to sustainable practices. The threat of negative media publicity can erode a firm's legitimacy and lead to public and regulatory pressures for change. For example, high-profile environmental incidents like oil spills (Paine et al., 1996) or industrial accidents (McGuire et al., 2022) can trigger public outrage and demand for stricter regulations (Burgherr, 2007; Chen et al., 2019), pushing organizations to adopt more sustainable approaches.

Organizations facing coercive pressures are motivated to demonstrate their commitment to sustainable development to protect their reputation and maintain legitimacy in the eyes of stakeholders (Peng, 2003). This pressure can drive firms to invest in sustainable initiatives, improve environmental performance, and engage in transparent reporting practices (Bansal, 2005) to align with societal expectations and regulatory requirements (Helfre & Boot, 2013).

Matten & Moon (2008) have investigated the different adaptations organizations made when facing coercive pressures in the United States and Europe. The authors have found that differences in political systems between the United States and Europe have influenced CSR practices. European governments have historically been more engaged in economic and social activities, sometimes mandating corporations to assume responsibility for health and pensions. In contrast, the United States has allowed for greater corporate discretion due to less government intervention. Variances in cultural systems have led to different assumptions about society, business, and government between the U.S. and Europe. Americans are seen as having a relative capacity for participation and philanthropy, scepticism about big government, and confidence in capitalism. The authors also highlight that educational and professional authorities play a role in setting standards for organizational practices. In Europe, leading business schools and higher education institutions have increasingly included CSR in their curriculum, exerting normative pressures on businesses. The authors argue that this trend has contributed to the shift towards explicit CSR in Europe.

Mimetic isomorphism, another mechanism identified by DiMaggio & Powell (1983), arises from organizations imitating the actions of successful peers in the face of uncertainty. When confronted with ambiguous situations or lacking clear guidelines, organizations tend to emulate the practices of established entities within their field (Benner & Veloso, 2008). Outcome salience and uncertainty play crucial roles in influencing the imitation behaviour of organizations in inter-organizational settings (Haunschild & Miner, 1997). Outcome salience refers to the visibility and prominence of the outcomes after other organizations adopt a particular practice or structure. These positive or negative outcomes influence whether an organization will imitate the practice. Outcome salience leads to selective imitation based on the perceived consequences of the practice rather than the characteristics of the organizations using it.

Another important contribution by Haunschild & Miner (1997) is the understanding of how uncertainty shapes imitation behaviour. Greater uncertainty shifts the balance between different modes of imitation. It enhances the impact of frequency and trait imitation but reduces or leaves unaffected outcome imitation. Uncertainty can lead organizations to rely more on imitation as a mechanism for decision-making in ambiguous or unpredictable environments.

The mimetic behaviour serves as a strategy to reduce uncertainty and mitigate risks by following the perceived successful strategies of others (Liang et al., 2007). As a result, organizational structures and practices become more homogenized as a consequence of mimetic isomorphism, leading to a convergence of behaviours and norms within a particular industry or sector (Bansal & Roth, 2000). Ma et al. (2021) mentioned that companies in the shipping industry faced mimetic pressure to adapt their operational practices in response to the implementation of emissions-controlled areas (ECAs) and low-sulphur regulations. This pressure likely influenced companies to exhibit mimetic behaviour by following industry norms and best practices to comply with regulations and similarly optimize their operations to their competitors.

Normative isomorphism, the third type of isomorphic process that leads to isomorphism of organizations, is closely linked to professionalization within organizational fields (DiMaggio & Powell, 1983). Institutional theory provides valuable insights into how organizations are influenced by normative pressures and legitimated elements, shaping their behaviour and practices (Zucker, 1987). Normative pressures that can influence organizations include external regulations and laws imposed by the state, professional standards and certifications, social expectations and cultural norms, and industry best practices. By understanding and responding to these normative pressures, organizations can enhance their legitimacy, reputation, and long-term survival in their respective environments (Oliver, 1991).

Professional standards, norms, and values play a significant role in shaping organizational behaviour and structure (Greenwood et al., 2002). Professionals within a specific occupation collectively strive to define the conditions and methods of their work, establishing a cognitive base and legitimation for their autonomy (Benner & Veloso, 2008). This process involves a struggle to control the production of their profession and negotiate with non-professional stakeholders. The growth of professional networks and the diffusion of new models across organizations contribute to normative isomorphism, creating a pool of individuals with similar orientations and dispositions across various organizational settings (Arregle et al., 2007).

Professional associations face the challenge of establishing and maintaining legitimacy in the eyes of their members, stakeholders, and the broader professional community (Greenwood et al., 2002). This pressure for legitimacy often drives organizational development efforts, leading associations to adapt their structures, practices, and strategies to align with prevailing professional norms and values. Greenwood et al. (2002) provide insights into how professional associations shape organizational development by legitimating change, endorsing local innovations, and, thus, contributing to transforming organizational practices and structures. The authors point out five main mechanisms of normative pressures: establishing norms, training and education, certification and licensing, monitoring and enforcement, advocacy, and representation.

Neo-institutional theorists defined later external pressures as mechanisms in three different types of institutions: regulative, normative, and cultural-cognitive (Scott, 2008). They differ on their basis of compliance, mechanisms, and legitimacy. Regulative institutions comply by expedience, using the mechanisms of coercion, sanctions, and incentives, and are legally sanctioned. Normative institutions comply with social obligations under normative pressure and are morally governed and regulated by rules, values, and behaviour. Cultural-cognitive institutions comply through shared understanding, using the mechanisms of mimetic, learning, and imitation, and drawing legitimacy from cultural support, systems of beliefs, models of reality, and guiding principles (Geels, 2020). The organization-centric view of classic institutional theory shifted from isomorphism to the broader concept of organisational fields, a system comprised of actors, actions and relations, including "firms, consumers, government actors, regulatory bodies, lobbying groups, unions, professional and trade organisations, organised public opinion and social pressure groups" (Geels, 2020, p.8). Neo-institutionalists' work, the economic evolutionary theory and the sociology of innovation landed the basis for the MLP view of sustainability transitions (Köhler et al., 2019). It complements the institutional theory in important ways, by adding technology and innovation as a centrepiece of sustainability transitions.

2.3 Multi-Level Perspective on Transition to low-carbon Fuels

This subsection summarizes the extensive body of literature about the transition to low-carbon fuels within the maritime industry through the lenses of the multi-level perspective of sustainability transitions in transportation (Ferrer & Thomé, 2023). The multi-level perspective (MLP) is a framework for understanding and analysing the dynamics of large-scale socio-technical transformations required for sustainability.

Sustainability transition research evolved in four theoretical streams: transition management (TM), strategic niche management (SNM), MLP, and technological innovations systems (TIS) (Köhler et al., 2019). TM suggests that policymakers can induce transitions. TIS theorists contribute to the idea that the development of new technologies comprises technologies, actors and institutions. SNM researchers see radical innovations emerging from "protected spaces" (e.g., demonstration projects, experiments, the Army) before selection to enter the mainstream market. They all have interfaces with the MLP framework, which sees transitions as the arena where innovations developed in niches struggle with and finally enter the dominant regime or fail, under the external pressures of the landscape. The concepts of incumbent regimes, niches, and landscapes are central to the MLP and SNM views (Kivimaa et al., 2019). This subsection briefly reviews them through the lens of MLP.

Sustainability transitions, under MLP, are socio-technical systems "since the fulfilment of societal functions involves not only technologies, but also situated consumer practices, cultural meanings, public policies, business models, markets, and infra-structures" (Geels, 2019, p.187). Social-technical systems emerge from human actors in social groups who share roles, responsibilities, norms, beliefs, behaviours, and perceptions, among other characteristics in common (Geels, 2004).

The MLP analyses the dynamics between niches, where innovation occurs, and socio-technical regimes, where incumbent firms and dominant technologies lie. This dynamic of changes is situated under a broader socio-technical landscape, defining the modus operandi and the boundary conditions about how niches and regimes interact during the transition (Geels, 2011).

Figure 1 presents a graphical representation of the socio-technical landscape, regime, and niches as described in the MLP framework. The outermost ellipse represents the socio-technical landscape, setting the broader contextual conditions and external pressures. Within this landscape, the socio-technical regime is depicted as an inner ellipse, embodying the established systems including dominant technologies and incumbent firms. Arrows within this regime illustrate the flow and interaction of elements within this system, highlighting its inherent stability and resistance to change.

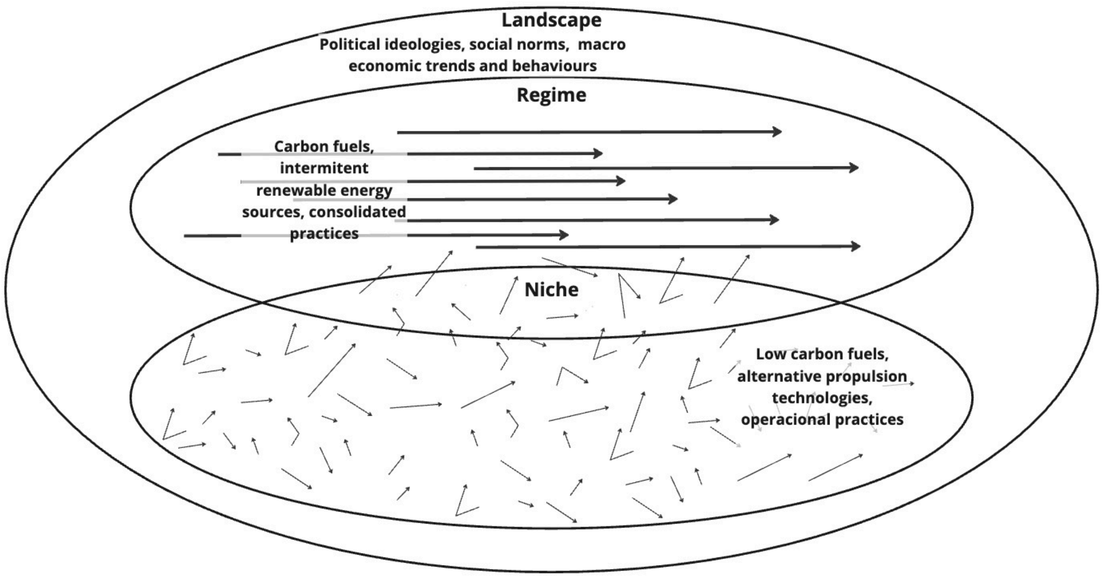

Figure 1: Conceptual representation of the MLP.
Source: Adapted from Ferrer & Thomé (2023).

MLP focuses on the interactions and dynamics between these three levels: niches, regimes, and landscapes. Niches are protected spaces where radical innovations can develop without the pressure of market selection. They serve as incubators for new technologies, practices, or social innovations that deviate significantly from the dominant regime. Niches are characterized by a small network of actors who support these innovations through funding, development, and early adoption. They allow trial and error, including investors and early adopters, challenging and eventually replacing dominant regimes (Geels, 2002).

Regimes are the dominant socio-technical systems with structured rules, practices, and norms, supported by policies, regulations and social norms, focusing on incremental improvements and involving a wide range of actors, such as industries, policymakers and consumers. Regimes create the selection environment that niches must navigate to achieve wider market adoption (Smith et al., 2005). Regimes are path-dependent because of several lock-in mechanisms, such as sunk investment, low cost and economies of scale of prevailing technologies, social and cognitive routines and mind-sharing constituting a social capital with user practices and lifestyles linked to particular technologies (e.g., the use of combustion engines), institutional and political regulations, standards, networks, lobbying, hindering innovation (Geels, 2019).

Landscapes are the exogenous context influencing and shaping regimes and niches. This level includes macro-level trends and structures such as cultural values, economic trends, wars, political developments, economic conditions, and environmental changes not under the agents' control. Landscapes are typically slow to change but can exert significant pressure on regimes, creating windows of opportunity for niche innovations (Geels & Schot, 2007).

Sustainability transitions are distinct from other technological transitions in three main aspects: (i) they are purposeful and related to collective goods; (ii) they embrace an ecological rather than a short-sided economic view, offering in the short term less cost-effective solutions than the prevailing dominant solutions; (iii) they apply to domains (e.g., transport, energy) led by large incumbent firms, possessing costly exploration, production, and distribution assets (Ferrer & Thomé, 2023; Verbong & Geels, 2007). Therefore, sustainability transitions call for a larger involvement of public authorities and civil society, changes in economic conditions (e.g., taxes and regulations), and the participation of incumbent firms (Geels, 2011, p.25). Sustainability transitions include the interplay of technology, power, economics, and cultures.

According to the MLP, sustainability transitions are a long-term endeavour encompassing major structural changes in transport, energy, the agri-food industry, construction, and other systems. These changes involve technology, policy, markets, consumer behaviour, infrastructure, culture, and scientific knowledge. They require the combined action of stakeholders from different firms and industries, policymakers, politicians, consumers, international organizations, governments, NGOs, engineers, and academics from several related areas (Markard et al., 2012; A. Smith et al., 2010). Figure 2 illustrates the evolution in time of alternative fuels viewed under the MLP lenses.

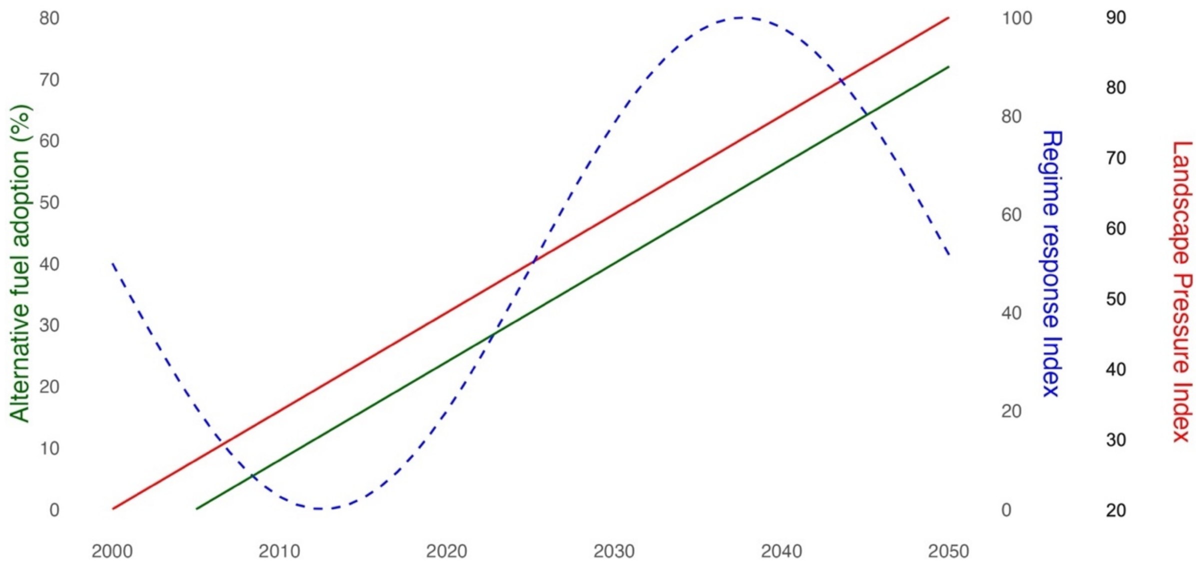

Figure 2: Adoption of alternative fuels in the maritime industry, regime responses, and landscape pressures over time.
Source: Use authorized by Ferrer & Thomé (2023)

The sine curve represents the socio-technical regime responses to the external pressures exerted by the landscape (in the red line), and the green line indicates the entrance into the regime of alternative maritime fuels. Regime switches occur when the continuous line crosses the sine curve and establishes a new regime. The sine is purposively drawn to show that sustainability transitions are not linear, and drawbacks might occur. Much attention has been paid to regime shifts. Smith et al. (2005) propose four phases of transitions: (i) purposive, (ii) endogenous renewal, (iii) reorientation of trajectories, and (iv) emergent transformation. Their typology is based on low-high coordination and internal-external use of resources (knowledge and production). Geels & Schot (2007) also describe four phases based on alignments and temporality: (i) technological substitution, (ii) regime transformation, (iii) regime reconfiguration, and (iv) de-alignment and re-alignment. The pathways have different actors, interactions and characteristics. In technological substitution, incumbent and entrant firms interact under market competition and power struggles. Transitions through transformation involve the regime and outsiders (social. movements), and under criticism, incumbents adjust rules. In transitions by reconfiguration, regime actors and suppliers interact, with the regime adopting innovations from new suppliers, which compete with old suppliers.

Finally, in de-alignment re-alignment, new niche actors create strong pressure on the regime, the incumbent loses legitimacy, and multiple novelties occur simultaneously. The emergence of alternative maritime fuels might occur in any of the four transition modes, depending on landscape changes, the number of alternative fuels offered by the new entrants, and the strength of the incumbent regime's resistance.

Another striking feature of MLP is its foothold on empirical research. Geels (2002) described the time elapsed in transportation, of 110 years to evolve from sailing ships to steamships in the UK marine, 70 years from horse-drawn carriages to internal combustion engines and 40 years to switch from piston planes to jet planes in the US. The British transition in the maritime industry is worth commenting further, based on Geels' (2002) case study. Sailing ships prevailed in the 1850s and 1860s. Steamships already existed but were restricted to inland waterways or in ports to manoeuvre large ships (niches). The British government created steamship subsidies to expedite the Empire's courier communications in 1938. The subsidized market formed a community of steamship builders, incentivizing innovations in steam and ironworking technologies. With the political revolutions and the famine in Ireland (1845-1849), the landscape change further propelled the steamship industry due to large migration flows to the US. The mass migration from Europe to the US created a "window of opportunity" for the steamship industry, facilitated by technical innovations (screw propellers, coal efficiency, iron hulls), allowing the building of larger vessels. The diffusion accelerated with the opening of the Suez Canal, which provided more direct routes to India and China. The socio-technical regime changed under the external pressure of landscape changes and for economic reasons. The incumbent industry reacted with more efficient and larger sailing ships until the old regime technology was replaced and a new regime was established.

Meanwhile, substantial infrastructural changes had to be made to expand ports and create coal infrastructure worldwide. New machines were created for loading and unloading cargo, and shipbuilding yards were transformed. Geels (2005) described similar long-lasting transformations in infrastructure during the transitions from animal traction to internal combustion and piston to jet planes.

In a nutshell, transition trajectories occur with the innovation of technologies and business models in the niches and in the R&D departments of incumbent firms. Sustainability transitions are marked worldwide by long-term landscape paradigm shifts, as encapsulated in the 2015 Paris Agreement and the Net Zero policies (Rajamani, 2019). Other landscape changes might be abrupt, like in wars and terrorist attacks, as in 9/11 in the US and the Russian-Ucranian war. The innovation enters the incumbent regimes. The incumbent firms resist the evolutionary trajectory Of new entrants because they are locked in existing assets, sunk operational costs, dominant technologies, and business models (Unruh, 2000). The struggle between niches and regimes is governed by the exogenous context of landscapes comprised of the long-term "technical and material backdrop that sustains society (…), demographic trends, political ideologies, societal values, and macro-economic patterns" (Geels, 2011, p.28). Sustainability pressures emanate from the landscape and stakeholders in regimes and niches. Under the initial MLP papers (Geels, 2004; Geels & Schot, 2007; Verbong & Geels, 2007), radical changes initiate in niches and incremental ones in the regimes. Later, the MLP view incorporated a more nuanced understanding of this bottom-up approach, describing radical innovation also initiated in the regime, for example, with the production of biomass electricity in replacement of fossil fuel in The Netherlands in the early 1990s (Raven, 2006), and describing innovations initiated by intermediaries in the regime as well as in niches (Mignon & Kanda, 2018).

MLP has a global model, seeing transitions under the lenses of the interactions between landscape, regime, and niches and a local-level analysis of activities and causalities. This dissertation spouses the global model with a long-term perspective of sustainability transition in maritime fuels.

The focus of combining Institutional Theory with MLP is on synthesizing the diverse perspectives and findings from various studies that have examined the significant shifts of sustainability transitions, emphasizing the technological, regulatory, and economic aspects, stakeholder involvement, decision-making processes, and practical implications of adopting alternative maritime fuels that influence this transition. Table 1 summarizes the similarities and complementarity between the two theories, abstracted from the papers reviewed in Subsections 2.2 and 2.3.

Table 1: Similarities and complementarity between the Institutional theory and MLP.

Similarities	
Institutional Theory	**MLP**
Focus on rules, norms and beliefs of social behaviour and institutional change.	Emphasizes the stability of regimes and the slow pace of change.
Analyse the micro (individuals), meso (structures) and macro (fields or sectors) levels.	Analyse transitions at the micro (niches), meso (regimes) and macro (landscape levels.
Institutional entrepreneurs are change agents.	Actors in niches and regimes interact and struggle for change or maintain the status quo.
Describe how institutions resist due to path dependence and legitimacy.	Describe lock-in and path dependence.
Complementarities	
Institutional Theory	**MLP**
Explains institutional context, including norms, values and cognitive frameworks	Focus on technological and socio-technical transitions.
It shows how actors actively change institutional structures through diffusion, translation, and institutional work, enhancing the understanding of lock-out mechanisms.	Describe stages and pathways for locking out of the incumbent regime.
Emphasizes institutional entrepreneurship, explaining how innovations gain legitimacy and overcome incumbent regimes.	Innovation occurs in niches and the R&D of some incumbent firms.

2.4 The use of theories in systematic literature reviews

This subsection provides a brief account of the use of theories in systematic literature reviews, outlining what constitutes a contribution to theory because the scoping and literature reviews are central to this dissertation. For a definition of a “good” theory, the reader is referred to Wacker (1998, 2008), Weick (1989, 1995) and Whetten (1989). This subsection outlines the types of theoretical contributions that literature reviews can provide to analyse alternative fuels in the maritime industry, which is a mature field of research with several reviews published. The analysis of the published reviews was the object of the tertiary literature review provided in Appendix D.

When contributing to theories, two main decisions are involved: (i) which type of literature review to choose and (ii) the level of maturity of the research field (Durach et al., 2021). The contributions to theories in this subsection are largely inspired by the work of Durach et al. (2021) and Seuring et al. (2021).

Grant & Booth (2009) distinguish 14 types of literature reviews, each serving a specific purpose. Its advantages and inconveniences are inspired by previous research by Torraco (2005) descriptions of methods and purposes of integrative reviews, Thomé et al. (2016) guidelines for systematic literature reviews in supply chain and operations management research, and the PRISMA statements and guidelines for systematic literature reviews.

Advantages and inconveniences focus on the type of outputs from the analysis, which, for Torraco (2005), can be a classification or taxonomy, a research agenda, a framework or a meta-theory. The guidelines from Thomé et al. (2016) and the PRISMA guidelines (Parums, 2021; Rethlefsen et al., 2021; Sarkis-Onofre et al., 2021) emphasize rigour and the steps of the research protocol, guiding the analysis of the inconveniences of the different type of literature reviews (quality, exhaustiveness, representativeness, transparency, objectivity, traceability, and reproducibility). Table 2 depicts the purpose, advantages and inconveniences of the literature reviews offered in this dissertation.

Table 2: Types of literature reviews.

Types of literature reviews	Purpose	Advantages	Inconveniences
Scoping review	Preliminary assessment of a research field, usually mapping authors, journals, themes and methods.	Quick and can be done with available software, expediting the analysis and providing the basis for classifications, research agendas, frameworks, and meta-theories.	Lacks the depth of analysis of evidence synthesis or systematic reviews. Does not assess the quality of primary studies with the same rigour as in systematic literature reviews.
Systematic review	Systematically search for the existing	Reports what is known, gaps, classifications,	Choice of databases might bias the

Types of literature reviews	Purpose	Advantages	Inconveniences
	literature adhering to guidelines, standards and research protocols.	frameworks, research agendas, and meta-theories in a transparent, objective, traceable, and reproducible way.	selection, search keywords might artificially limit the scope, and it might lack synthesis and contributions to theory.
Mixed studies / mixed methods review	Combination of qualitative (usually systematic) and quantitative reviews (usually bibliometric).	Provides a rich literature analysis and correlations among topics or categories. It applies the rigour of systematic reviews in a transparent, objective, traceable, and reproducible way.	Requires separate searches for qualitative and quantitative analysis over an extended period.
Umbrella or tertiary review	A review of reviews usually addressing mature research fields with several available reviews.	Provides classifications, research agendas, frameworks and meta-theories.	Is limited to published reviews and does not include primary studies.

Source: Adapted from Grant & Booth (2009).

According to Durach et al. (2021), the types of contributions a literature review can make to theories lie in the intersection between the literature review type and the maturity of the theory. A mature theory establishes “for whom,” “in what circumstances,” and “when” a phenomenon is observed, as the two theoretical lenses exposed in Subsections 2.2 and 2.3 do.

Durach et al. (2021, p.1098) propose three types of reviews that contribute to a theory: inductive theory building (inductive exploring), contextualized explanations and theory testing (both explaining a phenomenon), and interpretive sensemaking (exploring subjective realities). Mature theories are prone to theory testing, sensemaking, and, to a lesser extent, contextualized explanation.

Largely inspired by the works of Wacker (1998) and Weick (1995), Seuring et al. (2021) explore the four basic elements of a theory: definition, boundaries and limitations, variables and casualties, and predictions, offering a template to summarize the contribution. The types of contribution for Seuring et al. (2021) are theory building (inductive logic), theory modification (abductive logic), theory refinement (deductive logic), and theory extension (borrowing theories from other fields, enriching the field and broadening the theoretical repository). Table 3 displays the template offered by Seuring et al. (2021).

Table 3: Elements of theory building.

Element of Theory	Description
Definition (who and what)	A clear definition of the field's terminology should include who and what questions and outline what is not included.
Boundaries and Limitations (when and where)	The specification of boundaries and limitations establishes where and when a concept or construct could be applied and where not.
Variables and Causalities (why and how)	Variables and causalities should answer why and how a phenomenon occurs. They are more straightforward in quantitative research and less clear-cut in qualitative research. These questions guide the logic (inductive, abductive, deductive) applied in the analysis.
Predictions (could, should and would)	The theory should allow the prediction of events. The questions could, should, and would drive future research and analytical frameworks depicting the interrelationship among variables, explaining how a phenomenon could be or would be.

Source: Adapted from Seuring et al. (2021).

This research contribution to theory is outlined in the discussion and conclusion Chapters of the dissertation.

3 Methodology

This dissertation adopts a sequential exploratory mixed-method approach to explore the complexities of decarbonising maritime transportation. The methodology is structured to leverage the complementary strengths of qualitative and quantitative research methodologies, aiming to provide a holistic understanding of the factors influencing the adoption of sustainable fuels within the maritime industry. It is inspired by ontological positioning, institutional theory, and the MLP, reviewed in Chapter 2.

Figure 3 highlights the interconnection of the worldviews, strategies of inquiry and research methods.

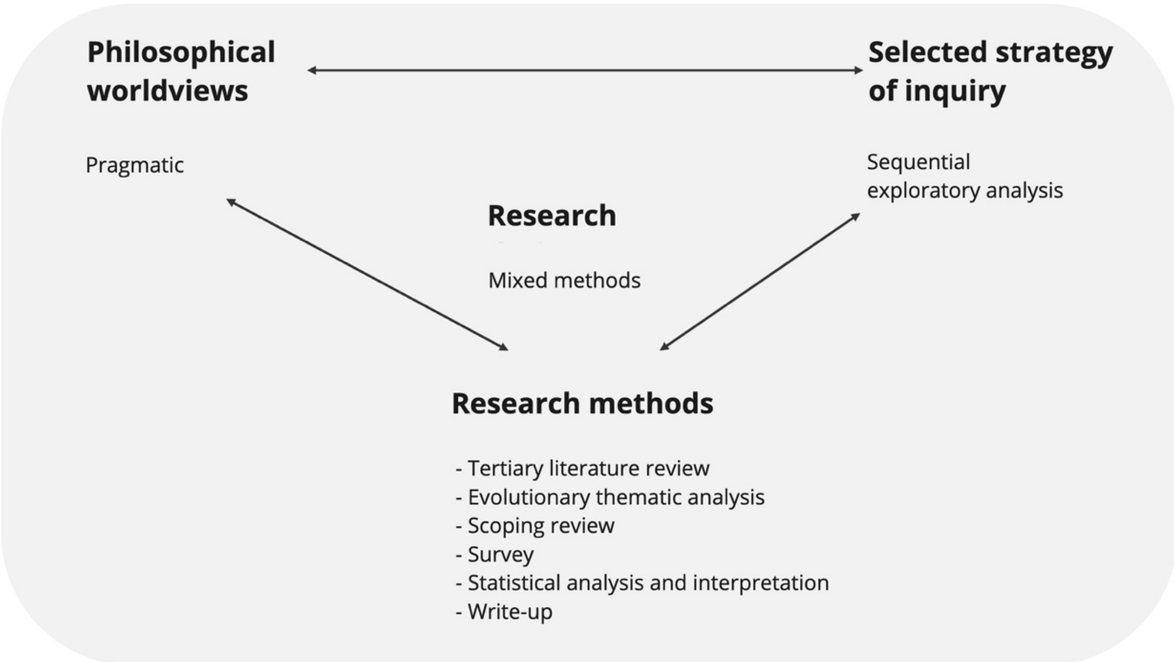

Figure 3: The research design.

The study's first phase utilises qualitative methods to gather deep insights into the prevailing conditions and nuanced factors that shape the maritime sector's environmental strategies, niches, social-technical regime and social-technical landscapes. This foundation enables the formulating of comprehensive research questions that guide the subsequent quantitative phase. Here, broader empirical analysis is employed to validate and expand the qualitative findings, ensuring a robust examination of the research questions.

Incorporating mixed methods enriches the research by providing both breadth and depth in data collection and analysis and addresses the limitations associated with using a single method. By intertwining qualitative and quantitative approaches, the study achieves a balanced view that captures the complex interplay of factors at work. This methodological synergy is depicted in the sequential integration of the study's phases, with each phase building upon the insights of the previous one, thus enhancing the overall validity and reliability of the findings. Subsection 3.1 describes the research design, followed by the research methods in Subsection 3.2.

3.1 Research Strategy Design

Qualitative and quantitative research methods have limitations that researchers need to consider (Creswell et al., 2007). On the one hand, while valuable for exploring complex phenomena in-depth and capturing rich, detailed data, qualitative research may be criticised for its potential subjectivity and lack of generalizability due to its small sample sizes and context-specific findings (Corbin & Strauss, 2008). On the other hand, quantitative research, known for its ability to provide numerical data and statistical analysis for making predictions and generalisations, may face limitations in terms of potentially oversimplifying complex phenomena, overlooking contextual nuances, and not fully capturing the depth and richness of human experiences (Johnson et al., 2007). Researchers need to be aware of these limitations and carefully consider the strengths and weaknesses of each method when designing their research studies to ensure a comprehensive and rigorous approach to data collection and analysis (Creswell, 2010).

As discussed by Jick (1979), the mixed-method approach arises from recognising the limitations inherent in single-method designs. By combining qualitative and quantitative methods through triangulation, researchers aim to address these weaknesses and enhance their research findings' credibility, validity, and reliability. It was Denzin (1978) who first outlined how to triangulate methods. Denzin defined triangulation as "the combination of methodologies in the study of the same phenomenon" (p. 291). Integrating diverse data sources allows for a more comprehensive understanding of complex phenomena, enabling researchers to gain deeper insights and richer explanations (Johnson et al., 2007).

Through triangulation, researchers can creatively innovate their methodological approaches, balancing conventional data collection methods with inventive techniques to capture the nuances of the research problem (Denzin, 1978). This approach increases confidence in research results and promotes a holistic view of the phenomena under study, emphasising the importance of leveraging the strengths of qualitative and quantitative methods to achieve a more nuanced and insightful analysis (Creswell & Plano Clark, 2017). According to Creswell & Plano Clark (2017), there are three basic types of mixed methods designs, with some other types of variants: (i) Convergent, also known as parallel or concurrent, designs are utilised when the objective is to integrate simultaneous quantitative and qualitative data to meet the objectives of the study. In this approach, data collection occurs concurrently, and the analysis involves merging and comparing these datasets and their findings; (ii) sequential, also referred to as explanatory sequential or exploratory sequential, designs facilitate a phased data collection approach where one phase builds upon the results of another. For instance, qualitative data might be gathered to explore the mechanisms behind quantitative findings (Klassen et al., 2012). Alternatively, preliminary qualitative insights can inform the creation of a quantitative survey intended for a broader demographic, and (iii) embedded or nested designs combine quantitative and qualitative methods, integrating one within the other to enhance understanding or refine concepts.

An example of this could be conducting detailed interviews during an intervention to understand participants' experiences with the treatment better. Care must be taken to consider the relationship between the different approaches to data collection, and a clear relationship between the two should be established (Goldkuhl, 2012). Klassen et al. (2012) call this relationship "the point of interface" and define it as the location where integration happens, and it may vary based on the design of the mixed methods.

This specific point can manifest during data collection, analysis, and/or interpretation (Klassen et al., 2012). When discussing the mixed method approaches, Mitchell (2018) points out that the method is useful when unexpected results arise from a prior study stage. They can help to deepen an understanding of quantitative findings or increase the generalizability of qualitative findings.

They can also help design and validate research instruments, such as questionnaires or complex interventions that will be used in further studies (Johnson et al., 2007). The weaknesses of mixed method studies can be related to the complexity of setting up such studies and the need for research to acquire expertise in various methods. It can also be difficult to decide when to proceed with sequential designs and how to mix, merge or combine qualitative and quantitative data (Creswell & Plano Clark, 2017).

This research design chooses to use quantitative data to support the study's qualitative findings. The sequential exploratory strategy is frequently recommended when a researcher must create a new instrument due to the inadequacy or unavailability of existing ones (Creswell, 2010). This strategy employed a three-phase approach where, initially, qualitative data was collected and analysed (Phase 1). The insights from this analysis were then used to develop a survey instrument (Phase 2), which was later distributed to a sample from the target population (Phase 3) (Creswell et al., 2007). The visual model for the research is shown in Figure 4.

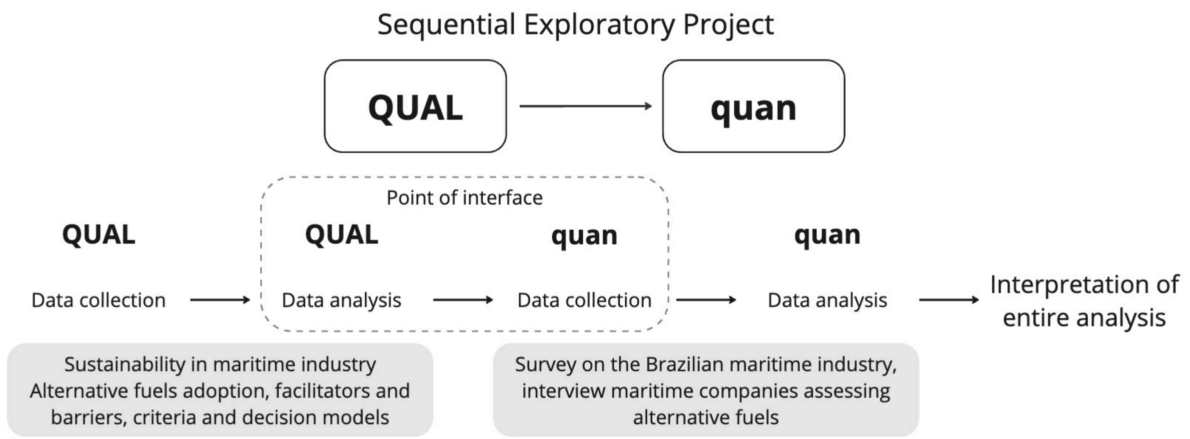

Figure 4: The visual model of the sequential exploratory project.
Source: Adapted from (Creswell, 2010).
Notes: A "→"indicates a sequential data collection form, with one form building upon another.

Capitalisation in Figure 4 indicates the weight or priority of the data, analysis, and interpretation of the study. "Qual" and "quan" are qualitative and quantitative, respectively. The boxes highlight the quantitative and qualitative data collection and analysis. The qualitative research is emphasised in the study, as shown by the capital letters. Qualitative research was employed to explore, structure and frame the research problem. The quantitative phase builds upon the findings from the initial qualitative phase. The quantitative stage is useful for expanding the initial understanding of the problem. The mixing or "point of interface" (Klassen et al., 2012) of the qualitative and quantitative methods occurred during the qualitative analysis of the data (Creswell, 2010, p. 243), where the data extracted from the qualitative studies was applied to conceive and structure the instruments to the quantitative methods, to retrieve quantitative data and information from the respondents. Specifically, data from the qualitative analysis were used to structure the survey questionnaire and the interview script and provided a contextual understanding that supported the statistical analysis of the survey. This approach enriched the depth of analysis and ensured that the quantitative data reflected the complexities uncovered in the qualitative phase.

The sequential exploratory strategy employed in this dissertation has proven effective in leveraging the strengths of qualitative and quantitative research methodologies. By beginning with an in-depth qualitative analysis, this study was able to build a robust framework for the subsequent quantitative phase, ensuring a deeper understanding of the research problem and enhancing the development of a specifically tailored research instrument (Creswell, 2010). A more comprehensive analysis of the research topic was obtained by integrating quantitative and qualitative data to support and expand the initial qualitative findings. Challenges related to the complexity of managing dual methodologies and the time-intensive nature of sequential phases were addressed through detailed planning and clear delineation of each research phase, ensuring that transitions were smooth and each phase informed the subsequent one effectively (Creswell & Plano Clark, 2017).

3.2 Research Methods

This Subsection will detail the specific methodologies employed in each phase, demonstrating how they were integrated at various points to ensure a robust and coherent approach to tackling the research questions. This section aims to illustrate the practical application of the mixed-method framework in comprehensively understanding the topic. The process of undertaking a pragmatic study is first to identify and view a problem within its broadest context (Glasgow, 2013). The broadest context leads to research inquiry, which seeks to understand better and ultimately solve the problem. A pragmatic piece of research may involve multiple methods in combination in a pragmatic order to advance a specific piece of research in the best possible manner (Popa et al., 2015).

In this dissertation, a sequential exploratory mixed-method approach was implemented to address the complex issue of decarbonising maritime transportation, aiming to complement the strengths of both qualitative and quantitative research methodologies, as shown in Figure 5.

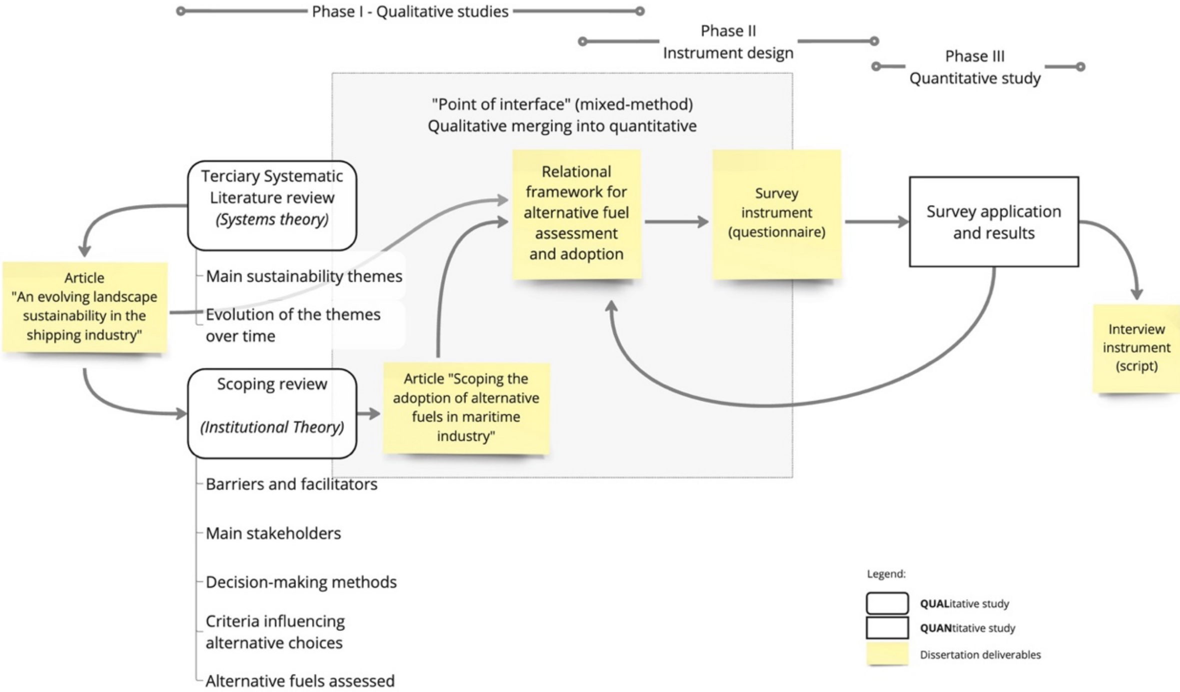

Figure 5: General dissertation research design.

The initial qualitative phase was crucial for understanding the current landscape in-depth and identifying key themes and factors influencing sustainable fuel adoption within the maritime industry. These insights then informed the design and structuring of the subsequent quantitative phase, which aimed to validate and expand upon the qualitative findings through broader empirical analysis.

Qualitative methods were applied to collect and analyse the data from the literature to address the following research objectives, (i) map the main research themes in sustainability in the maritime industry; and, (ii) identify and analyse enablers and barriers to adopting sustainable fuels in maritime transportation.

A tertiary systematic literature review (SLR) and a scoping review addressed the two distinct, specific, yet connected topics. The methods of the tertiary review are described in Appendix D. It was submitted for publication in a first-tier journal (CAPES Qualis A1) and is presently under review. The scoping review method is detailed next.

3.3 Scoping review for the adoption of sustainable fuels

A scoping review study is an approach to reviewing documents that involves summarising a range of evidence to convey the breadth and depth of a field (Levac et al., 2010). It is a method used to map the literature on a specific topic or research area. It aims to identify key concepts, gaps in the research, and types and sources of evidence to inform practice, policymaking, and further research (Daudt et al., 2013). Scoping studies differ from systematic reviews in that they do not typically assess the quality of included studies, and they also differ from narrative or literature reviews as the scoping process requires analytical reinterpretation of the literature (Arksey & O'Malley, 2005).

According to Arksey & O'Malley (2005), there are six stages proposed to conduct a scoping review: (i) identifying the research question; (ii) identifying relevant studies; (iii) study selection; (iv) charting the data; (v) collating, summarising, and reporting the results; (vi) consulting with stakeholders.

These stages provide a structured approach to conducting a scoping review and help ensure the rigour and comprehensiveness of the synthesis process.

By promoting clear and transparent reporting of scoping review findings, researchers can enhance translating the synthesised knowledge into practice, policy, and further research (Colquhoun et al., 2014). This translation can contribute to the impact and relevance of scoping reviews in informing decision-making processes.

This scoping review is then motivated by the need to systematically map the barriers, facilitators, stakeholders involved, criteria and decision methods adopted by the maritime industry to adopt or assess alternative low-carbon fuels. To this end, this scoping review examines 641 papers on the various methods, barriers and enablers adopted by maritime industry stakeholders to assess a wide range of alternative fuels. It focuses on fuel type analysis, stakeholder involvement, decision-making processes, and the interconnections among these elements to develop a logical framework for evaluating best practices in maritime environmental policy. The review also explores the broader social, environmental, and economic factors that influence the adoption of low-carbon fuels.

To fulfil the stages (ii) and (iii) of the framework proposed by Arksey & O'Malley (2005), this scoping review searched for relevant studies in the main academic databases where documents on the topic of maritime operations, sustainability, decision-making are indexed, namely Scopus and Web of Science

(Zhu & Liu, 2020). A search strategy was developed and tested for several combinations of keywords and logic. After several attempts and tests, the most successful strategy is exhibited in Figure 6 below. This search string was applied to both databases, searching in the fields of title, abstract, and keywords and all fields for Scopus and Web of Science, respectively.

> (barrier* OR challenge* OR hinder* OR opportunit* OR facilitator OR criteria) AND (maritime OR ship) AND (fuel) AND (sustainab* OR green OR alternative)

Figure 6: Final search string adopted for the scoping review.

The study selection was an important step in the screening process. A large number of studies was retrieved from the initial search strategy. A *post hoc* criteria for inclusion and exclusion was defined after becoming familiar with the literature (Arksey & O'Malley, 2005). The criteria aided in eliminating studies that were not central to the interest of this study; the inclusion criteria applied in this scoping review related to the maritime industry, fuel assessment, assessment of sustainable alternatives, and adopting any decision-making tool or framework. The exclusion criteria were, (i) articles not in the English language; (ii) document type other than articles; and, (iii) documents not related to the maritime industry.

The inclusion and exclusion criteria were applied to all citations, and the first screening was applied to title and abstract reading. A stratified random sample based on the publishing decade was applied to the result of the screening process. Stratified sampling is a technique used to divide a population into distinct subgroups or strata based on specific characteristics relevant to the study. In this case, the 297 articles were stratified by the decade of publication, creating strata for each decade from the 1970s to the 2020s. This approach aims to ensure that each decade is adequately represented in the sample, making it more representative of the entire population. This approach is particularly important when some decades have more articles than others. After dividing the population into these decade-based strata, a random sample was selected from each stratum. The sample size from each decade was proportional to the number of articles in that decade, ensuring accurate representation, see Table 4. This method guarantees that the diversity and trends across different decades are accurately reflected in the sample.

Table 4: Results of the stratified sampling technique.

Periods	Population size	Number of samples
1973-1979	1	1
2000-2009	13	4
2010-2019	71	21
2020-2024	212	64

Notes: The decades of 1980 and 1990 did not retrieve any documents.

Copies of the full articles were downloaded for the articles sampled from the random selection. During this phase, nine articles could not be retrieved for scope review. Then, after the stratification, another sampling without replacement was conducted to guarantee the number of samples analysed in the synthesis. The several steps undertaken to achieve the final sample of documents for full reading and scoping review are detailed in the PRISMA flow diagram in Figure 7.

The next stage of the study involved ‘charting’ key information items from the primary research articles reviewed. As defined by Ritchie & Spencer (1994), charting is a technique for synthesising and interpreting qualitative data by sifting, charting, and sorting material according to key issues and themes. This process takes a broader view, recording information about the ‘process’ of each program or intervention to contextualise its outcomes. In this study, data were charted using a customised data charting form in Excel, capturing general study information and specific details. This charting included the citation, main theme, focus on the maritime industry and low-carbon fuels, stakeholders highlighted, decision-making processes or models mentioned, handling of identified pressures, prioritised decision criteria, assessed fuels and conclusions, barriers to low-carbon fuel adoption, and enablers or positive influences. This structured approach ensured uniformity and comprehensiveness in analysing the 90 articles sampled, even when some reports lacked specific details.

The next stage of the scoping study involved collating, summarising, and reporting the results. An analytic framework was developed to present a narrative account of the literature, including basic numerical analysis and thematic organisation. The numerical analysis mapped the distribution of studies by type of fuel and decision models adopted, highlighting dominant fuels of interest and the most applied models for decision-making. This structured approach provided a comprehensive review identified research gaps and offered insights to aid in adopting low-carbon fuels.

A scoping review involves a structured approach (Arksey & O'Malley, 2005) that starts with formulating a clear and comprehensive research question. This question should be broad enough to cover the full scope of the topic while being specific in defining the concept, target population, and outcomes of interest. The initial stage also involves setting clear objectives for the review and outlining expected outputs. The next step is identifying relevant studies through a well-planned search strategy. Once relevant studies are identified, the selection process involves applying predetermined inclusion and exclusion criteria to ensure that only pertinent studies are considered. The criteria are applied by data charting, where key information like study characteristics and findings are systematically extracted and organised.

The subsequent stage involves collating, summarising, and reporting the results to highlight common themes, patterns, and any notable gaps in the literature. Finally, consulting with stakeholders validates the findings and enhances the review's relevancy and applicability to real-world scenarios. This structured framework, enhanced by inputs from various experts and stakeholders, ensures that a scoping review comprehensively maps out key concepts and evidence within a specific field or area of research.

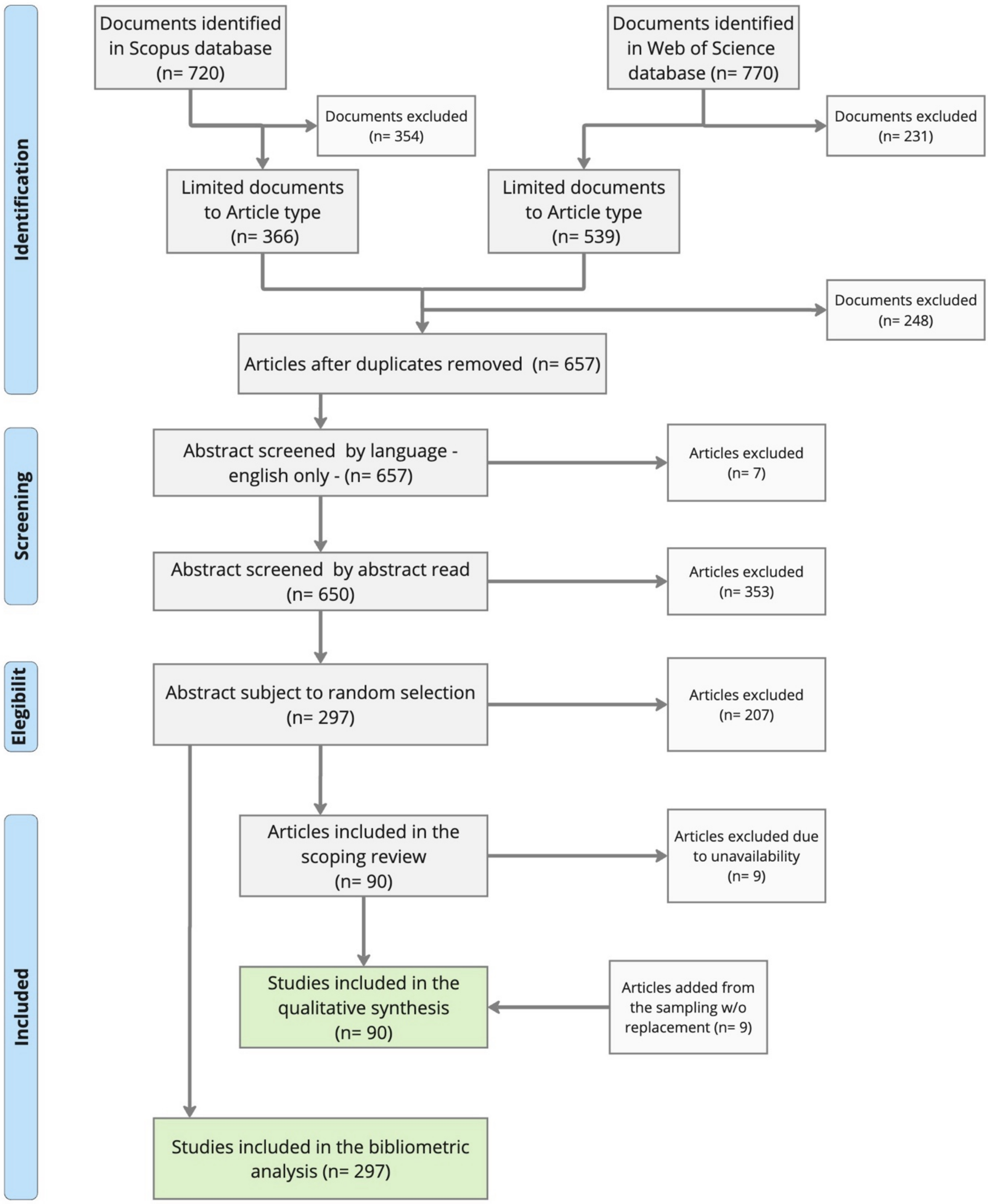

Figure 7: PRISMA flow diagram.
Source: Adapted from Tricco et al. (2018).

3.4 Survey Design

The quantitative survey conducted as part of this master's thesis is predicated on insights gained from prior qualitative studies within the maritime industry, focusing on adopting sustainable practices. These preliminary studies provided a critical foundation by identifying key concepts and variables that influence sustainability in maritime operations, which were further explored and quantified through the survey. The survey aimed to measure and confirm the relationships between these variables, offering a more structured and statistically valid understanding of how sustainability practices are implemented and perceived in the maritime sector. This research phase is instrumental in translating qualitative insights into empirical data that can substantiate theoretical models of sustainable practice adoption in maritime logistics.

This survey was designed to capture a comprehensive view of the operational, regulatory, and economic dynamics that influence adopting Sustainable purchasing practices (SPP) and other sustainable practices among Brazilian maritime organisations. By integrating established theoretical frameworks such as Institutional Theory, the survey assesses how normative, coercive, and mimetic pressures shape organisational strategies and outcomes in Brazil's unique institutional and economic landscape. Inspired by MLP's sustainability transitions approach, the survey also focused on technologies and alternative maritime fuels.

The selection of Brazil as the sampling setting for this research is strategically justified by its significant position within the global maritime industry and the comprehensive regulatory framework governing its maritime operations (Moura & Andrade, 2018). As the largest ship-owning country in South America and ranking 29th worldwide with a substantial fleet, Brazil plays a pivotal role in international maritime logistics, particularly in transporting major commodities (UNCTAD, 2023). This extensive involvement in global trade makes Brazil an exemplary context for exploring how local and international regulatory pressures influence the adoption of sustainable practices (UNCTAD, 2020).

Furthermore, the Brazilian maritime sector operates under robust environmental and safety regulations, including the Environmental Crimes Law, the Oil Law, and various Maritime Authority Standards. These regulations exemplify the coercive pressures that compel maritime organisations to adhere to stringent environmental and safety standards. The study's focus on respondents across various roles related to procurement within the maritime industry's value chain allows for a nuanced analysis of how these regulatory frameworks impact the sustainability strategies of maritime organisations. This setting provides a unique opportunity to assess the effectiveness of sustainable procurement practices in a highly regulated environment, offering valuable insights locally and globally.

A conceptual model was established as the foundation for the empirical investigation into adopting Sustainable purchasing practices within the Brazilian maritime industry, as shown in the schematic diagram in Figure 8. This model was developed following established methodologies (Forza, 2002) and served to structure the theoretical constructs—variables crucial to understanding the dynamics of SPP implementation.

Figure 8: Schematic diagram of the theoretical framework of the survey.

This diagram not only visualises the hypothesised links but also serves as a guide for the empirical investigation based on the Institutional theory and MLP, ensuring that each aspect of the model is thoroughly explored through the survey design as follows:

a) Institutional Pressures are categorised into coercive (e.g., government regulations), normative (e.g., industry standards), and mimetic (e.g., benchmarking against industry leaders) pressures that influence organisations' sustainability practices;
b) Sustainable purchasing practices (SPP) encompasses practices like setting sustainability goals, training on sustainability impacts, integrating sustainability into procurement processes, including sustainability clauses in contracts, and developing focused purchasing policies;
c) Organisational performance: Refers to the environmental, economic, and operational impacts of adopting SPP practices.
d) Services like maintenance, fleet repair, dredging, port infrastructure, and alternative fuels.

The relationships among these constructs are hypothesised as follows. Coercive pressures are expected to directly influence adoption of internal and external SPP practices due to regulatory compliance needs. Normative pressures are posited to enhance the integration of sustainability into procurement processes, motivated by ethical standards and industry norms. Mimetic pressures encourage adopting SPP practices modelled after successful implementations observed in leading companies, promoting a culture of sustainability. The adoption of SPP practices (both internal and external) is hypothesised to positively impact organisational performance across environmental, economic, and operational dimensions.

The proposed relationships are grounded in Institutional Theory, which suggests that organisations conform to the expectations of their institutional environments to gain legitimacy, access resources, and enhance survival prospects (Greenwood et al., 2002; Kern, 2011; Meyer & Rowan, 1977; Zucker, 1987). By aligning SPP practices with these pressures, maritime companies comply with external expectations and internalise these practices as strategic components of their operations, leading to improved sustainability outcomes.

These relationships were expected to manifest within the context of the Brazilian maritime industry, which is characterised by stringent environmental regulations, a strong emphasis on ethical operations, and a competitive landscape that encourages benchmarking and best practices. The study focused on organisational-level responses to institutional pressures and recognising variations based on company size, market position, and strategic priorities.

Services like maintenance, fleet repair, dredging, port infrastructure, and alternative fuels were assessed based on the MLP framework.

The chosen unit of analysis was the organisation, specifically companies within the Brazilian maritime industry. The research objective drove this selection to explore how coercive, normative, and mimetic institutional pressures affect organisational decisions regarding adopting Sustainable purchasing practices. Focusing on the organisational level allowed a comprehensive analysis of systemic behaviours and strategies that companies employed in response to these pressures. It aligns with the nature of the surveyed data, which gathered responses from knowledgeable individuals about their organisations' procurement practices, thus reflecting the strategic choices of these entities rather than personal opinions or actions. By analysing organisations as the unit of analysis, the study effectively captured the complex interplay of external and internal factors influencing sustainability in procurement practices across the maritime sector.

The survey targeted respondents who are directly involved in or knowledgeable about the procurement processes within their organisations, ensuring that the data collected was reliable and valid. An electronic invitation to participate in the survey was sent to a curated list of 782 professionals, chosen based on their expertise, experience, and relevance to the study's focus. Broadening the respondent base was recognised, and a wide spectrum of industry perspectives was incorporated. The invitation was subsequently extended to 456 associates of the Brazilian Society of Naval Engineers (Sociedade Brasileira de Engenharia Naval - SOBENA), an organisation comprising professionals dedicated to the advancement of naval architecture and maritime engineering in Brazil. The Sobena e-mail to its associates is provided in Appendix A. A total of 90 questionnaires were completed and returned.

Given the limited number of survey responses (n=90), establishing a definitive relationship among the elements of the Institutional Theory framework proved challenging. Consequently, this study adopted a descriptive approach (Forza, 2002) to quantify the relevance of facilitators and institutional pressures to adopting sustainable practices within the Brazilian maritime industry. This methodological shift enabled a more flexible exploration of data, allowing for the identification of emergent patterns and insights that may not strictly conform to the initial theoretical predictions.

This flexible framework still utilises the constructs of institutional theory and MLP as a guiding lens for the discovery of unexpected linkages and influences. Data analysis involved descriptive statistics and thematic analysis to uncover prevalent trends and respondent perceptions. This approach enriched the study by capturing a broader spectrum of organisational behaviours and industry-specific challenges related to sustainability. The findings were then discussed in the context of existing literature, highlighting both the unique contributions of this research and areas where further inquiry is needed. This pragmatic approach aligns with the mixed-methods design (Goldkuhl, 2012; Mitchell, 2018; Popa et al., 2015) by allowing the research to remain adaptable and responsive to the data as it unfolds, ensuring that the study effectively addresses the real-world complexities and nuances of the maritime industry's sustainability practices. This flexibility in methodology validates the research process and enhances its relevance and applicability to the practical demands and evolving dynamics of the field.

This survey sought to ascertain the stability of responses related to sustainability practices and perceptions by comparing mean values across various dimensions of SPP practices and institutional pressures. The dataset was segmented based on the survey completion dates, dividing responses into two groups, considering the median date from the first response to the last response. Utilising the Mann-Whitney U test to evaluate differences between these groups across 21 variables, the analysis revealed no significant disparities at the $p<0.05$ significance level, which excludes the non-response bias.

A comprehensive pre-test was conducted to enhance the survey's accuracy and prevent the inclusion of biased or confusing questions. Two senior industry specialists reviewed and commented on the questionnaire, whose insights were used to refine our survey instrument.

In a commitment to uphold the highest ethical standards, all respondents signed an informed consent form. This measure was taken to guarantee the anonymity of participants and confidentiality, thereby minimising the risk of receiving biased or socially desirable responses.

This multi-faceted approach, combining rigorous statistical analysis with proactive quality assurance measures, underscores the robustness of the study's findings and its contribution to sustainability practices within the supply chain management domain.

The survey instrument for this study was crafted to ensure precise data collection that aligns with the empirical demands of exploring the Institutional Theory within the Brazilian maritime industry. The survey began with the collection and development of measurement items grounded in a comprehensive literature review. The scoping review was further refined through consultations with practitioners in the maritime sector. This iterative process ensured that constructs such as Sustainable purchasing practices, facilitators, services, and products were theoretically sound and practically relevant.

For data collection, the survey utilised a structured format with carefully worded questions to minimise ambiguity and avoid biases such as leading or loaded questions (Forza, 2002). Questions were formulated to be clear and concise, with a limit of 20 words where possible, to ensure they are easily understandable by respondents without misinterpretation. The closed questions facilitated straightforward responses that could be efficiently coded and analysed while ensuring that the responses were mutually exclusive and collectively exhaustive (Flynn et al., 1990). The scaling methods were selected for their ability to capture the intensity of respondents' attitudes towards sustainability practices and their perceived importance in organisational and procurement contexts.

The survey instrument was divided into five sections, as shown in Figure 9. Each designed section investigated different aspects of sustainable purchasing practices: initial questions assessed the current importance of sustainability versus its importance in the future; subsequent items queried the existence and development of specific SPP practices within the respondents' respective companies; and later sections evaluated the significance of sustainability in product and service procurement and the strength of internal and external enablers influencing SPP adoption. This comprehensive structure facilitated ease of response and ensured that the survey effectively captured the complex interplay of factors influencing SPP adoption in the Brazilian maritime industry. A detailed explanation of each section and the adopted scales are described in Figure 9.

The first section of the survey was designed to evaluate the current and future relevance of sustainability within the procurement decisions of respondents' organisations. This section presented two statements for respondents to assess their level of agreement using a five-point Likert scale, ranging from 1 (do not agree at all) to 5 (completely agree). The first statement, "My organisation considers sustainability in its purchasing decisions," aimed to capture the present consideration of sustainability factors in procurement processes. The second statement, "Sustainability will have an increasing influence on my organisation's purchasing decisions," was intended to gauge the respondents' perception of the growing importance of sustainability in future procurement strategies.

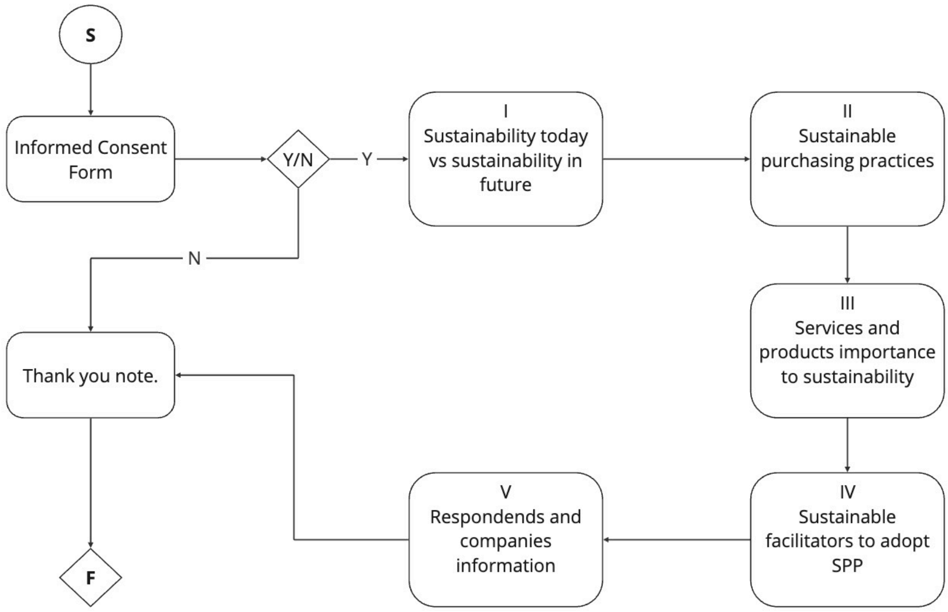

Figure 9: Survey instrument flow.
Legend: S: Start; F: Finish.

To ensure clarity and a common understanding among respondents, key terms were defined at the beginning of the survey, as shown in Figure 10 and Figure 11

> ‘Sustainability’ (Alhaddi, 2015; Norman & MacDonald, 2004) was defined as encompassing environmental, social, and economic factors, such as carbon and waste reduction, water efficiency, diversity, promotion of well-being, equal opportunities, and the development of a strong, stable, efficient, and fair economy.

Figure 10: Definition of sustainability for this survey.

> ‘Sustainable Purchasing’ was described as acquiring goods and services to minimise the impact on society and the environment throughout the product’s lifecycle.

Figure 11: Definition of sustainable purchasing practices for this survey.

These definitions were provided to deepen respondents’ understanding of sustainable practices adopted by companies, ensuring that responses were informed and aligned with the study’s objectives. These definitions were presented at the beginning of the survey.

The sustainable purchase processes (SPP) were assessed in the second section of the survey. Table 5 shows a summary of the data collected.

On the one hand, six SPPs, namely Developed goals for sustainable purchasing (DGSP), training for purchasing employees on sustainability impacts (TPES), integration of sustainability into the procurement process (ISPP), sustainability clauses in contracts (SCC), written policy on sustainable procurement (WSP), measures to develop sustainability-focused purchasing policies (MDPP) can be adopted and controlled autonomously by the company, thus are defined as internal practices. On the other hand, Supplier sustainability information (SSI), supplier sustainability development (SSD), ISO14001 certification (ISO-Cert), and preference for highly-rated sustainability suppliers (PHRS) requires interaction with and assessment of external parties, thus are defined as the four external practices.

In this section, ten sustainable practices were presented, and respondents were asked to answer if their company had such practice in place (Yes or No), if it was under development, or even if they didn't know about it.

For the third section, based on the MLP framework, respondents evaluated the significance of sustainability in acquiring specific products and services, thereby capturing a comprehensive view of procurement priorities within the industry (Polo, 2012; Widyaningsih et al., 2022). This questionnaire section assessed the interaction between niches and the incumbent regime's services and products, a centrepiece of MLP. A five-point Likert scale was adopted, ranging from 'not at all important' (1) to 'very important' (5). The list of ten products and /or services are:

a) fuels and lubricants;
b) spare parts for vessels;
c) safety equipment;
d) maintenance services;
e) information technology systems;
f) shipbuilding and repair;
g) dredging services;
h) port infrastructure;
i) sustainable office materials;
j) communication equipment.

Table 5: Sustainable purchase practices adopted in the survey.

Sustainable purchase practice	Description
Developed goals for sustainable purchasing (DGSP) -I	Strategic objectives set by an organisation to guide its purchasing decisions towards sustainability. E.g.: targets for reducing environmental impact, enhancing social responsibility, reducing carbon emissions.
Training for Purchasing Employees on Sustainability Impacts (TPES) - I	Involves educational and training programs to promote awareness of sustainability among procurement staff. The aim is to equip these employees with the knowledge and skills needed to make informed decisions that align with the company's sustainability goals.
Integration of Sustainability into the Procurement Process (ISPP) - I	Reflects the extent to which sustainability criteria are embedded into the procurement policies and procedures of an organisation. It represents the systematic inclusion of environmental and social considerations in all stages of the procurement process.
Sustainability clauses in contracts (SCC) -I	Refers to specific provisions and requirements included in procurement contracts that obligate suppliers to adhere to certain sustainability standards or practices. These clauses ensure that the company's sustainability goals are upheld throughout the supply chain.
Written policy on sustainable procurement (WSP) = I	Involves formal policies that outline the principles and guidelines for implementing sustainable procurement practices. A written policy helps standardise sustainability efforts across the organisation and communicates the company's commitment to sustainable procurement to all stakeholders.
Measures to Develop Sustainability-Focused Purchasing Policies (MDPP) – I	Actions taken to create and refine purchasing policies that prioritise sustainability. It includes the development of frameworks and tools to facilitate sustainable purchasing decisions within the organisation.
Supplier sustainability information (SSI) – E	Involves gathering detailed information about the sustainability performance and practices of suppliers. It includes assessing suppliers' environmental impacts, labor practices, and corporate social responsibility initiatives.
Supplier sustainability development (SSD) – E	Refers to efforts made by the purchasing organisation to help suppliers improve their sustainability practices. It can involve providing training, resources, or support to help suppliers align their operations with sustainability standards.
ISO14001 certification (ISO-Cert) – E	ISO 14001 is an internationally recognised standard for environmental management systems. This assess the companies which have obtained ISO 14001 certification, indicating their commitment to systematic environmental management.
Preference for highly-rated sustainability suppliers (PHRS) - E	Involves choosing suppliers based on their sustainability performance ratings. It reflects a preference for working with suppliers who are recognised for their superior sustainability practices and achievements.

Notes: Practice domain: I = Internal to the company; E=External to the company.

In the fourth section, the questionnaire sought to identify facilitators' importance and strength in adopting SPP based on a view of internal and external forces (DiMaggio & Powell, 1983). These enablers resulted from the scoping review performed in previous stages of the dissertation. Respondents rated the potency of these enablers on a similar five-point scale ranging from 1=very weak to 5=very strong, allowing for differentiation in the perceived influence of each force. Table 6 lists these facilitators, their classification into internal and external and their respective citations in the literature.

Table 6: Internal and external enablers to the adoption of sustainable practices.

Pressure	Facilitators	Citations
Internal		
	Company President's Vision	Hoskisson et al. (2000), Ma et al. (2021) and Raza & Woxenius (2023)
	Moral/Ethical Motivation	Nyuur et al. (2017), Surie & Ashley (2008) and Youngs (2010)
	Cost savings	Correa et al. (2019), Helgason et al. (2020) and Irena et al. (2021a)
External		
	Anticipated Government Legislation/Regulation	Ahn et al. (2019) and Gobbi et al. (2020)
	Current Government Legislation/Regulation	Ampah et al. (2021), Bayraktar & Yuksel (2023) and Bilgili & Ölçer (2024)
	Company Reputation	Dixon et al. (2016) and Vural et al. (2021).
	Customer Pressure	Kuo et al. (2022) and Raza & Woxenius (2023)
	Pressure from Third Parties	Foo et al. (2019), Meixell & Luoma (2015) and Zhu et al. (2007)
	Leadership in Best Practices	Foo et al. (2019) and Surie & Ashley (2008)

In the last section of the survey, respondents' identification was crucial, given the specialised knowledge required to provide accurate information about the company's procurement practices. It also allowed the identification of the samples to post-survey contact and the identification of the samples' interest in following up on an interview to comment and validate the results. The result of the form was published online in a Google form platform and may be accessed at:

https://docs.google.com/forms/d/1L7Uh_gr7XulB2dVRKAzjPOKficyg2MqBwZekRqFZkxU/edit.

The initial data analysis phase in this survey involved conducting descriptive statistics to understand the characteristics and properties of the collected data (Flynn et al., 1990). The descriptive analysis included assessing the central tendencies, dispersions, frequency distributions, and correlations of the data, as these measures provide crucial insights into the quality and structure of the dataset (Forza, 2002). The R programming language was applied to run these analyses, emphasising visual representation and graphical techniques to enhance the understanding and interpretation of the data.

The interpretation of the survey results moved the analysis from the empirical to the theoretical domain (Flynn et al., 1990), bridging the gap between observed data and theoretical expectations. A correlation analysis was undertaken to understand the relationships among respondents' perceptions of sustainability. However, interpretation also required careful consideration of potential statistical and internal validity errors and the implications these errors have for the study's findings in terms of statistical power, significance levels, and effect sizes (Forza, 2002). Internal validity was scrutinised to ensure that the causality inferred between variables like Sustainable Purchasing practices and organisational performance was robust, discounting alternative explanations (Flynn et al., 1990). A Wilcox test was conducted, dividing the sample into two subsets based on the submission date of the answers to assess the internal validity of the responses obtained in the survey. The test results revealed that no statistically significant differences were found between the two halves of the sample for any of the variables analysed, as can be seen in the Appendix B. This result suggests that the responses to the questions addressed in the questionnaire remained consistent over time, reinforcing the reliability of the collected data.

4 Results

This section comprises the results from the methods adopted in the research design, as detailed in Figure 5. In detail, it presents the results of the scoping review and survey.

The results of the tertiary review, co-occurrence of keywords, longitudinal research agenda, taxonomy for maritime sustainability, research trajectory, and framework are provided in the Appendix D.

4.1 Results of the scoping review

This scoping review has focused on systematically evaluating the literature to capture the main elements of the decision-making process of adopting alternative fuels in the maritime industry. Two analyses were undertaken in this study. First, a bibliometric review of 297 articles based on the co-occurrence of the keywords was undertaken to assess the conceptual structure of the decision-making process towards adopting alternative fuels in the maritime industry. Then, following the sampling process established in Figure 7, 90 articles were used to conduct a scoping review to answer the following *RQ3 - What are the barriers to and enablers of the adoption of sustainable fuels?* The results of both studies are presented in the following sections.

4.1.1 Coercive, mimetic and normative pressures in the maritime industry

The isomorphism of external pressures described by DiMaggio & Powell (1983) lays the ground for a better understanding of transitioning to low-carbon in the Maritime Industry.

4.1.1.1 Coercive pressures

Coercive pressures in the maritime industry arise from various sources at multiple levels, including international, regional, and local influences. These pressures are primarily exerted through regulatory frameworks, economic incentives, and enforcement mechanisms that compel maritime organizations to conform to established norms and practices. In international navigation, adherence to established global regulations is imperative for ensuring operational compliance across diverse maritime sectors. The IMO is an organization formed by the United Nations with the following purpose: "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, the efficiency of navigation and prevention and control of marine pollution from ships"(United Nations, 1948, p.1). Back in 1958, the year that the IMO convention entered into force, the original concern of the organization was mainly maritime safety. Soon after it began, it increased its scope of action to prevent sea pollution by oil. The institution's website reports 51 treaty instruments for the regulation of international shipping, and 21 of these are directly related to protecting the maritime environment (IMO, 2024b). With this mandate, regulatory power and influence, the IMO is the major source of coercive power in the international maritime industry (Helfre & Boot, 2013; Lindstad & Eskeland, 2016; Mallidis et al., 2020).

Three principal conventions predominantly govern the IMO regulatory framework: (i) the International Convention for the Safety of Life at Sea (SOLAS), which is dedicated to the safety of life and property at sea; (ii) the International Convention for the Prevention of Pollution from Ships (MARPOL), which focuses on the protection of the maritime environment from operational and accidental pollution; (iii) and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), which sets qualification standards for masters, officers, and watch personnel on seagoing merchant ships. Together, these conventions form the cornerstone of international maritime law, ensuring that the varied facets of maritime operations, from crew training to environmental protection, adhere to globally recognized standards.

The historical context surrounding maritime air pollution began with discussions at the 1973 MARPOL convention. However, specific regulations on air pollution were not included at that time. This issue was part of broader environmental concerns addressed by various international agreements, notably the 1979 Convention on Long-range Transboundary Air Pollution, the first legally binding treaty to address air pollution on a regional scale. Building on international efforts from the 1980s and 1990s, MARPOL Annex VI, adopted in 1997 and effective May 2005, extends these initiatives by setting strict emission limits and banning substances that deplete the ozone layer (IMO, 2024a). This regulatory framework is designed to mitigate the adverse effects of air pollution from ships, aligning with the evolving commitments of IMO Member States to protect human health and the environment from the impacts of global shipping emissions (Corbett et al., 2007).

The UN established the SDGs and the Sustainable Development Agenda for 2030, which include 17 objectives urging action from all countries. As the UN's operation arm, IMO is mandated to set global standards in maritime transport, playing a crucial role in supporting the implementation of the 2030 Agenda for Sustainable Development and SDGs. IMO's efforts include promoting safe, secure, clean, and efficient maritime transport for sustainable development. Considering specifically SDG 13 – "Take urgent action to combat climate change and its impacts", IMO has set an initial strategy and targets to reduce emissions from ships in 2018, aiming to decrease carbon intensity and enhance the use of alternative fuels (MEPC, 2018). Later, in 2023, the IMO updated its strategy, focusing on achieving at least 5% use of near-zero GHG emission technologies by 2030, aiming for 10%, and striving for net-zero GHG emissions from international maritime transport by 2050 (MEPC, 2023).

In terms of national regulations, IMO plays a crucial role in setting and enforcing environmental regulations for global shipping. The IMO's regulations, such as the MARPOL, address issues like sulphur oxide (SOx), nitrogen oxide (NOx), and greenhouse gas (GHG) emissions. Compliance with these regulations is complex due to flag states and flags of convenience (FOC), which can impact ships' credibility and compliance levels.

Another source of coercive pressure in the maritime industry is National regulations. As ships sail from one port to the other, each country has its own national regulations, setting stricter sailing and docking rules. Champ (2000) discusses the challenges and implications of national regulations on organotin, particularly tributyltin (TBT), in antifouling paints. The author evaluates the effectiveness and impact of national regulations on reducing organotin concentrations in the environment, focusing on these regulations' economic and environmental consequences. Champ's (2000) findings highlight that national regulations often prioritize short-term national interests, leading to unintended consequences (e.g. shifting antifouling repainting business to non-regulated countries). This shift results in economic losses for domestic shipyards in regulated countries as they struggle to compete with cheaper labour and less stringent environmental laws in non-regulated countries. This example is a clear and empirical demonstration of how institutions shape organizational practices oriented to comply with regulations and, at the same time, aim for economic outcomes. The author also points out that national regulations must consider their policies' global impact and encourage the development of sustainable and non-toxic alternatives to organotin compounds.

On the issue of plastic pollution in marine and coastal habitats Thushari & Senevirathna (2020) review scientific data on sources, impacts, and management initiatives at international, regional, and national levels. The study aims to provide insight into protecting ocean basins and coastal zones from plastic pollution. The authors review national polythene and plastic management regulations from the US, South Korea, Scotland and Sri Lanka. These national-level initiatives demonstrate efforts to mitigate plastic pollution through legislation and waste management practices, reinforcing the State's coercive and normative mandates. The study emphasizes the importance of addressing plastic pollution through strategies, including regulatory frameworks, public-private partnerships, awareness campaigns, and scientific research.

The IMO has proposed the establishment of ECAs to reduce sulphur oxide emissions in areas with dense ship traffic, such as ports. These are designated regions where ships must use fuels with a sulphur level of no more than 0.1% to limit sulphur emissions. Ships sailing in ECAs must comply with regulations mandating low-sulphur fuels to minimize environmental impact and improve air quality in these regions. Ma et al. (2021) addressed the challenge of simultaneously optimizing ship route, speed, and refuelling strategy in response to national regulations, particularly ECAs. The study developed a nonlinear mixed integer programming model to optimize these variables and proposed a solution algorithm for practical application. The research demonstrates that by optimizing these variables simultaneously, shipping companies can reduce costs significantly and comply with ECA regulations effectively. The authors emphasize that the regulatory environment, particularly the implementation of ECAs and low-sulphur regulations, has significantly shifted operational practices in the shipping industry. To comply with these regulations, shipping companies have had to adapt their operational practices by implementing fuel-switching methods, optimizing routes to minimize fuel consumption, and adjusting speeds to balance cost efficiency and environmental compliance.

National regulations also impact fuel supplies. Jeong et al.'s (2018) study aims to enhance the establishment of safety exclusion zones by examining the adequacy of current practices and regulations regarding LNG bunkering safety. The authors utilize scenario analysis, event tree analysis and risk assessment to identify potential risks associated with LNG bunkering accidents. The study references current standards (ISO, 2015) and common practices for LNG cargo transfer and bunkering to inform the scenario analysis and risk assessment. The study provides valuable insights into the regulators' determination of safety exclusion zones for LNG bunkering by evaluating accident risks and considering national regulations and standards. Results suggest that additional safety measures may be necessary for high-volume bunkering in high-density population areas, such as port cities.

Balcombe et al. (2019) explore various strategies for decarbonising the international shipping industry, considering fuels, technologies, and policies. The study aims to inform pathways for achieving decarbonisation, identify mechanisms with the greatest potential to reduce emissions and highlight critical research gaps. The authors state that policies are crucial in decarbonization efforts in the international shipping industry. Policies serve as key drivers for incentivizing and regulating emissions reductions, promoting the adoption of cleaner fuels and technologies, and shaping the overall trajectory towards a more sustainable shipping sector. The authors highlight that the lack of policies is a barrier, and effective policies (in place and working) are facilitators for decarbonising the shipping industry.

In terms of barriers, Balcombe et al. (2019) identify that a complex regulatory landscape, cost implications, and the lack of global consensus can delay and hinder the efforts to decarbonize the maritime sector. The complex international regulatory framework governing shipping can pose challenges for effectively implementing decarbonization policies. In particular, coordinating among various stakeholders and complying with diverse regulations can be daunting (Bloor et al., 2013; Di Vaio et al., 2021). Policies aimed at decarbonization may involve significant costs for shipping companies, especially when investing in new technologies, fuel and operational practices. Achieving global consensus on decarbonization policies can be challenging due to differing priorities, interests, and levels of commitment among countries (Ashrafi et al., 2020; Hezam et al., 2022; Sahnen, 2019).

As per the facilitators, Ampah et al. (2021) and Moshiul et al. (2023) claim that long-term vision, incentives, support, collaboration and engagement can leverage the implementation of decarbonization activities by the sector. Policies that provide a clear long-term vision and roadmap for decarbonization can facilitate industry planning and investment. Certainty and stability in policy frameworks enable shipping companies to make informed decisions and strategic investments. Policies that offer incentives, subsidies, or financial support for decarbonization efforts can encourage shipping companies to adopt cleaner technologies and fuels. In addition, financial incentives can help offset the costs associated with transitioning to low-carbon practices (Kern, 2011). Collaborative approaches involving industry stakeholders, policymakers, and regulatory bodies can facilitate the development and implementation of effective decarbonization policies (Moshiul et al., 2023). Engaging with key actors in the shipping sector can ensure that policies are practical, feasible, and aligned with industry needs (Morris, 2020; Videira et al., 2012).

Port authorities are another source of local coercive pressure. Daamen & Vries (2013) emphasize that port authorities play a significant role in the decarbonization efforts within the port-city interface. Port authorities are responsible for implementing strategies and initiatives to reduce carbon emissions and promote sustainability in port operations. Di Vaio & Varriale (2018) take it further and make ports the main regulatory institutions within seaports. They protect the environment, global climate, local communities, and society. Port authorities must implement measures to reduce and prevent the negative external effects of ports, e.g. pollution and environmental degradation. Poulsen et al. (2018) distinguish the port authorities' roles in facilitating environmental upgrading by describing four key actors. The landlords provide land and basic infrastructure. The regulators set tariffs and environmental standards for tenants and other port users and engage in spatial planning. The operators have their own fleets of harbour craft and equipment to provide safe fairways and basic infrastructure. The community managers bring together a variety of port stakeholders to improve collaboration and port performance. Di Vaio & Varriale (2018) suggest yet another distinct and important function, considering that port authorities must ensure a balance between the benefits and costs of port activities while also assuming a "regulator function" to ensure the safety and security of ship and cargo operations within the port in compliance with environmental and energy regulations and laws.

4.1.1.2 Mimetic pressures

In maritime shipping, cargo owners, as buyers of shipping services, play a significant role in driving environmental upgrading within the industry (Poulsen et al., 2016). Their sustainability commitments, efforts, and specific environmental demands can influence shipping companies to improve their environmental performance. Cargo owners, especially those with clear sustainability strategies and ambitious environmental targets, will likely be at the forefront of posing new environmental demands to shipping companies. As cargo owners start to place demands on shipping companies regarding their environmental performance, there is a growing trend of shipping organizations adopting similar environmental practices and initiatives to meet these demands (International Chamber of Shipping, 2023), a clear mimetic mechanism. This mimicry can be observed in the development of industry-led and multi-stakeholder initiatives on sustainable shipping and the implementation of green rating schemes within the maritime shipping sector (Godet et al., 2021).

Di Vaio et al. (2021) highlight that shipping companies adopt mimetic behaviours in response to the pressures they face in the industry to achieve sustainability and environmental performance. The authors identify some mimetic behaviours, such as adopting sustainable operations practices, participating in collaborative projects, establishing sustainable strategies, promoting responsible ship recycling, and focusing on inclusive culture and talent development.

Considering events causing supply chain disruption, Lee et al. (2023) analyse the COVID-19 pandemic and the rapid contraction of the global economy, which led maritime companies to respond to pressures. The authors suggest that companies adopt mimetic behaviours such as expanding the controlled fleet, increasing ship size, forming strategic alliances, conducting mergers and acquisitions (M&A), and establishing smart integrated land and marine logistics systems. These actions aim to provide competitive shipping services and ensure the companies' sustainability in the evolving global economy. Additionally, companies are encouraged to shift their focus from past ship operation management practices centred solely on financial value investments to the management of ship operations based on the new concept of combined Environmental, Social, and Governance (ESG) actions.

Shipping companies exhibit mimetic behaviours by emulating industry best practices, engaging in collaborative initiatives, adopting sustainable strategies, promoting responsible practices such as ship recycling, and focusing on talent development and diversity to respond to the sustainability pressures they face in the maritime industry. The alignment of voluntary "green shipping" initiatives with regulatory requirements is essential for driving further improvements in environmental performance (Christmann & Taylor, 2002; Godet et al., 2021), leading shipping organizations to follow similar paths towards sustainability.

4.1.1.3 Normative pressures

Normative pressures also play an important role in decarbonizing the maritime industry. One example of an external factor that has shaped the entire transportation sector worldwide was the terrorist attacks of 9/11 (Lun et al., 2008). The authors show how this heightened awareness has led to a greater emphasis on improving container transport security, with organizations facing pressure to enhance security measures to protect against potential threats and vulnerabilities. For example, the US Department of Homeland Security has set strategic goals for awareness, prevention, protection, response, and recovery in container transport security. The authors discuss the influence of institutional isomorphic processes on adopting technology for security enhancement in container transport chains. These processes pressure organizations to conform to industry standards and practices, leading to the adoption of technology solutions to improve security. The research suggests that organizations in the container transport industry face pressures to comply with regulations, ensure market acceptance, and legitimize the use of technology for security enhancement. These pressures significantly shape organizational development by influencing decision-making processes, resource allocation, and strategic planning related to technology adoption for security purposes.

Another relevant source of pressure that moulds organizational behaviour is insurance companies and their procedures, which are set by insurance premiums based on risk levels, directly influencing operational and safety practices. The insurance industry can shape organizational behaviour within the maritime sector by influencing incident reporting procedures and the overall safety culture (Hassel et al., 2011). By promoting a culture of transparency and accountability, insurance companies can encourage organizations to report incidents accurately and promptly, improving the quality of data in accident databases. Zhang & Lam (2017) discuss how the insurance industry can shape organizational behaviour by highlighting the importance of risk management and its impact on organisational decision-making. Insurance provides a safety net for businesses by mitigating potential risks and liabilities, influencing how organizations approach various aspects of their operations. With insurance coverage, organizations may feel more secure in taking calculated risks, exploring new opportunities, and making strategic decisions that align with their long-term goals.

Classification societies are crucial in the maritime industry (International Association of Classification Societies, 2024) to enhance safety and ensure compliance. The body of classification societies is responsible for (i) providing classification services, (ii) issuing statutory certifications, (iii) aiding the maritime industry, and (iv) developing and promoting technical requirements. The International Association of Classification Societies (IACS) also produces "position papers" on key topics for the industry, such as ballast water management, container ship safety, cyber systems, GHG emissions, new technologies and fuels, among others. Silos et al. (2013) emphasize the multifaceted role of Classification Societies. They perform important public functions related to ensuring maritime safety and preventing contamination, as well as complementing or supplementing the public activities of states in ensuring maritime safety and pollution prevention. Considering this important role in the industry, classification societies influence the governance of maritime safety by playing a key role in providing classification certificates to shipowners (Lissillour & Bonet Fernandez, 2021). These certificates are essential for ship operation as they are required to insure vessels or secure a charterer. Shipowners have no practical alternative but to contract with a classification society to obtain and maintain classification, giving these societies considerable influence in the maritime field (Lissillour & Bonet Fernandez, 2021).

Classification societies are essential for monitoring and inspecting vessels to maintain safety and compliance with regulations (Silos et al., 2013; Sotiralis et al., 2019). To meet the demands of classification societies, organizations have changed their behaviours by implementing self-regulation and working with recognized organizations (ROs), entities to which flag States delegate responsibilities related to the inspection and monitoring of vessels to ensure compliance with IMO regulations.

Discussing the commercial pressures faced by classification societies, Silos et al. (2013) focus on retaining sufficient customers to survive, leading them to compete to attract business. This competition can result in Classification Societies lowering their standards to attract customers, incentivising ship owners to switch between societies based on technical rigour or vessel age criteria. The authors also bring up the actions taken by the European Union to regulate the conditions classification societies must meet through directives to ensure independence and not influenced by owners or constructors. In regions where there is effective control of sub-standard vessels, ship owners tend to choose Classification Societies that are part of reputable international associations (Silos et al., 2013). This preference is influenced by the ship owners' fear of facing deficiencies or detentions by Port State Control (PSC) authorities. This decision-making process reflects the impact of globalization on the maritime industry, where adherence to recognized standards becomes crucial for maintaining operational efficiency and avoiding potential regulatory issues.

Addressing the complex regulatory framework and the role of classification societies to inform and influence, Lissillour & Bonet Fernandez (2021) highlight that they place a high value on publications to make public the consensus reached by their members and other actors in the industry. By issuing "Unified Interpretations" in response to vague regulations, classification societies provide guidance and clarity on compliance, influencing how organizations interpret and adhere to regulations. They explain their work favourably through publications in academic and mainstream journals, shaping the vocabulary and understanding of maritime safety within the industry.

4.1.2 Results of the Bibliometric Study

The distribution of articles produced per year, as shown in Figure 12, reveals a significant evolution in research interest and activity in the maritime industry's adoption of alternative low-carbon fuels. From 1974 to the early 2000s, there was minimal to no research output in this area, with only sporadic articles appearing. This period of relative inactivity highlights a lack of focus or awareness regarding low-carbon fuels within the maritime industry.

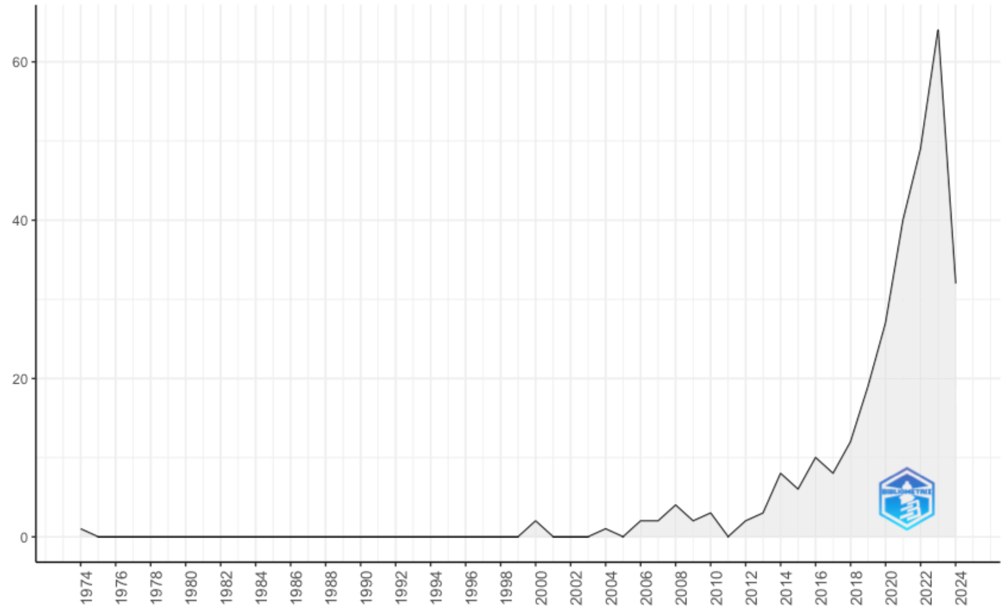

Figure 12: Annual scientific production.

However, starting in the mid-2000s, research activity has increased interest. The number of articles begins to rise steadily, particularly from 2008 onwards, reflecting growing global awareness and concern about environmental sustainability and the need for the maritime industry to transition to cleaner energy sources. This upward trend became more pronounced from 2014 onwards, with significant year-on-year increases in articles published.

The peak in research activity is observed in recent years, with a dramatic rise in publications from 2018 to 2023. The year 2023, in particular, shows a remarkable surge with 64 articles, the highest in the dataset, followed by 32 articles in 2024 up to the time of data collection. This surge likely corresponds to intensified global efforts to address climate change, stricter regulatory frameworks, and a growing consensus on the importance of sustainable practices in the maritime industry.

The most relevant sources contributing to the body of literature on alternative low-carbon fuels in the maritime industry, as shown in Figure 13, provide a diverse and comprehensive perspective on the subject.

As the leading source, the Journal of Cleaner Production (21 articles) focuses on sustainable production and environmental practices. Its many articles reflect its significant role in disseminating research on cleaner technologies and sustainable practices within the maritime industry. Energies (18 articles) covers various energy technologies and their applications, making it a crucial platform for research on alternative fuels.

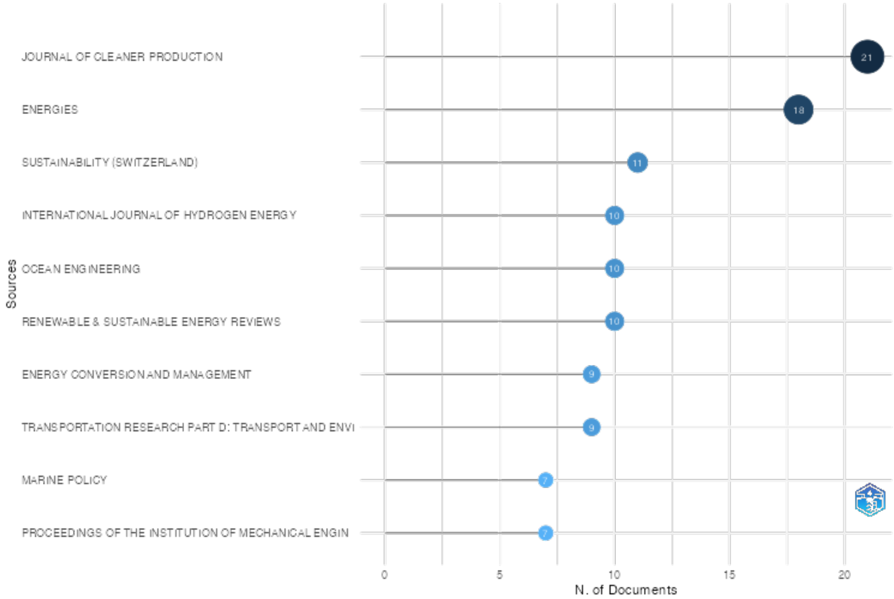

Figure 13: Most relevant sources.

The substantial number of articles indicates its relevance in exploring innovative energy solutions and their implementation in maritime contexts. Sustainability (Switzerland) (11 articles), known for its broad focus on sustainability, underscores the importance of integrating environmental, economic, and social dimensions in the transition to low-carbon fuels. The International Journal of Hydrogen Energy (10 articles) specifically focuses on hydrogen as an energy source, and the research published here explores the technical, economic, and environmental aspects of hydrogen energy. The Ocean Engineering (10 articles) addresses engineering solutions for marine environments. The articles from Ocean Engineering contribute to understanding the technical challenges and innovations in adopting low-carbon fuels in maritime operations, emphasizing practical engineering applications and solutions.

The Renewable & Sustainable Energy Reviews (10 articles) provide in-depth analyses of renewable and sustainable energy technologies. The presence of articles from this source highlights its role in synthesizing existing knowledge and identifying future research directions in the context of low-carbon maritime fuels. The Energy Conversion and Management (9 articles) focuses on the efficient conversion and management of energy. Its contributions are essential for understanding the efficiency and performance of various low-carbon fuels in maritime applications, offering insights into energy optimization and management practices. The Transportation Research Part D: Transport and Environment (9 articles) examines the environmental impacts of transportation. Its inclusion in the top sources indicates the importance of evaluating the environmental benefits and impacts of adopting low-carbon fuels in the maritime industry and understanding policy implications. The Marine Policy (7 articles) is known for its focus on maritime and coastal policies. This journal's articles are crucial for understanding the regulatory and policy frameworks that influence the adoption of low-carbon fuels. The Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment (7 articles) specializes in maritime engineering. The research it publishes offers detailed technical analyses and engineering solutions for integrating low-carbon fuels into maritime operations, highlighting innovations and practical challenges in this field.

The most relevant authors in the scoping review are listed in Figure 14. They have significantly contributed to the understanding of alternative low-carbon fuels in the maritime industry, focusing on various aspects such as emissions reduction, energy efficiency, and regulatory compliance. Their work collectively emphasizes the technological advancements, economic evaluations, and policy frameworks necessary for transitioning to sustainable maritime practices.

F. Ballini has contributed to optimizing decision-making for emissions reduction and analysing the trade-offs of cleaner seaborne transportation. His work on the optimal decision-making framework for Italian container terminals integrates economic, social, and environmental criteria to identify the best alternative energy sources. This comprehensive approach is exemplified in Ballini's collaboration on port emissions reduction schemes, highlighting the importance of policy instruments and collaborative efforts among stakeholders.

S. Brynolf has researched the environmental performance of alternative marine fuels. His studies, including lifecycle assessments of various fuels and propulsion systems, provide valuable insights into renewable methanol and hydrogen prospects. Brynolf's work underscores the need for policy initiatives to promote renewable marine fuels and highlights these alternative's economic and environmental benefits.

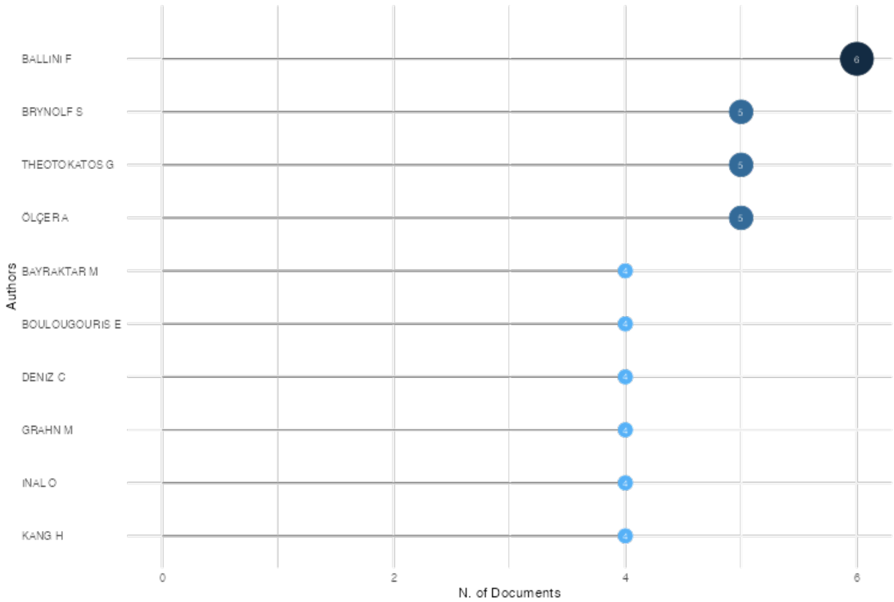

Figure 14: Most relevant authors.

G. Theotokatos focuses on optimizing ship energy systems and performance-emissions trade-offs. His work on dual-fuel engines and parametric investigations using CFD models provides detailed analyses of engine settings and their impact on emissions and fuel consumption. Theotokatos also explores hybrid power systems and their potential to achieve zero-carbon shipping, emphasizing the importance of integrating environmental and economic objectives in decision-making processes.

A. Ölcer has contributed to developing decision-making frameworks for evaluating cleaner transportation options. His research includes a comprehensive analysis of hybrid propulsion systems and the role of hydrogen in decarbonizing the shipping industry. Ölcer's work on technological solutions and policy implications provides a roadmap for achieving net-zero goals in maritime transport.

E. Boulougouris has focused on the safety and feasibility of alternative marine fuels. His comparative safety assessments of hydrogen and battery-powered systems for high-speed ferries highlight the critical safety considerations and potential risk mitigation strategies. Boulougouris' work emphasizes the need for detailed safety evaluations and regulatory frameworks to support the adoption of alternative fuels.

H. Kang has explored the risk analysis and thermodynamic performances of alternative fuels, such as ammonia and hydrogen. His studies on truck-to-ship ammonia bunkering and the integrated SOFC-GT systems for marine vessels provide valuable insights into the safety and efficiency of these alternative fuels. Kang's research highlights the potential of ammonia as a hydrogen carrier and its role in sustainable maritime operations.

H. Wang has conducted lifecycle analyses of hydrogen-powered marine vessels and optimal maintenance strategies for ship hulls. His work demonstrates hydrogen's environmental and economic benefits as a marine fuel and emphasizes the importance of proper maintenance in reducing operational costs and emissions. Wang's studies provide a holistic view of the lifecycle impacts and cost implications of adopting alternative fuels.

M. Grahn has focused on renewable marine fuel's lifecycle assessment and costs. Her research, including the environmental performance of fossil-free ship propulsion systems, provides comprehensive evaluations of the potential of electro-ammonia and hydrogen in reducing greenhouse gas emissions. Grahn's work highlights the importance of low-carbon electricity in achieving significant environmental benefits.

J. Lee has investigated strategic pathways to alternative marine fuels within the context of South Korea's shipping practices. His research addresses the sociotechnical challenges and opportunities of adopting LNG, methanol, ammonia, and hydrogen, emphasizing the need for collaborative governance and innovative strategies to facilitate the transition to sustainable fuels.

M. Bayraktar has explored the economic and regulatory aspects of converting marine diesel engines to methanol engines. His studies on the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations provide insights into the feasibility and benefits of using alternative fuels to meet stringent environmental standards. Bayraktar's work highlights the economic advantages and emissions reductions achievable through engine retrofits and the adoption of renewable methanol.

The most relevant affiliations contributing to the literature on alternative low-carbon fuels in the maritime industry reflect a global and interdisciplinary effort and are shown in Figure 15.

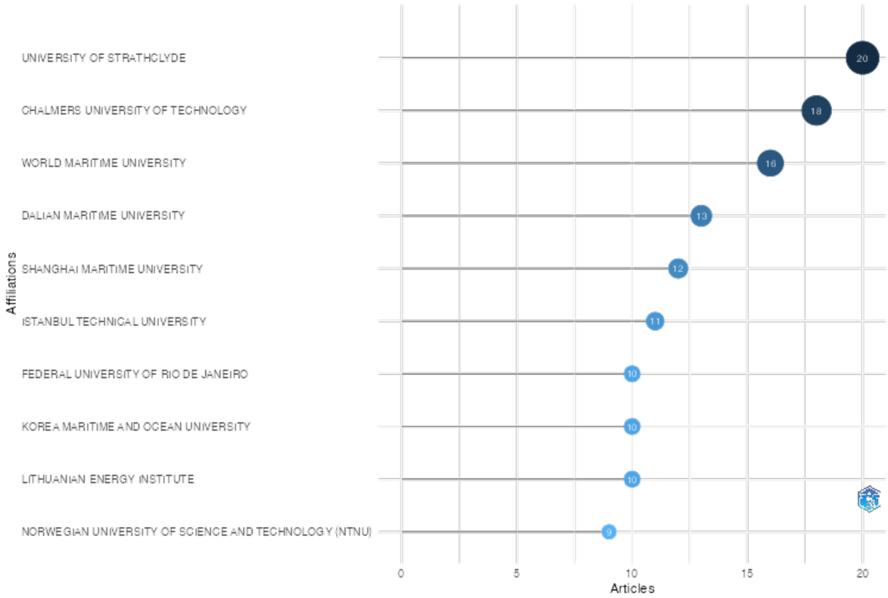

Figure 15: Most relevant affiliations.

The University of Strathclyde (20 articles) leads with strong engineering and technology research, providing insights into technical innovations and sustainable maritime practices. Chalmers University of Technology (18 articles) follows closely, and it is known for its focus on energy efficiency and sustainable maritime practices. The World Maritime University (16 articles) specializes in global maritime policies and regulatory frameworks. Dalian Maritime University (13 articles) and Shanghai Maritime University (12 articles), key institutions in China, contribute valuable research on maritime engineering and environmental sustainability. Istanbul Technical University (11 articles) offers insights into innovative engineering solutions and sustainable practices. The Federal University of Rio de Janeiro (10 articles) focuses on energy technology and environmental policy. Korea Maritime and Ocean University (10 articles) addresses the technical and policy challenges of low-carbon fuel adoption. The Lithuanian Energy Institute (10 articles) analyses energy systems and alternative fuels in depth. Finally, the Norwegian University of Science and Technology (NTNU) (9 articles) emphasizes sustainable energy solutions and the integration of low-carbon fuels in maritime operations. These affiliations highlight a diverse and comprehensive approach to advancing low-carbon fuels in the maritime industry.

The most cited papers in the scoping review encompass a range of crucial topics in the transition to alternative low-carbon fuels in the maritime industry, including bio-oil production, hydrogen integration, renewable energy systems, lifecycle assessments, and policy and economic considerations, as shown in Figure 16. These studies highlight the technological, economic, and regulatory challenges and opportunities in adopting sustainable fuel alternatives, emphasizing the need for a comprehensive and collaborative approach to achieving long-term environmental goals.

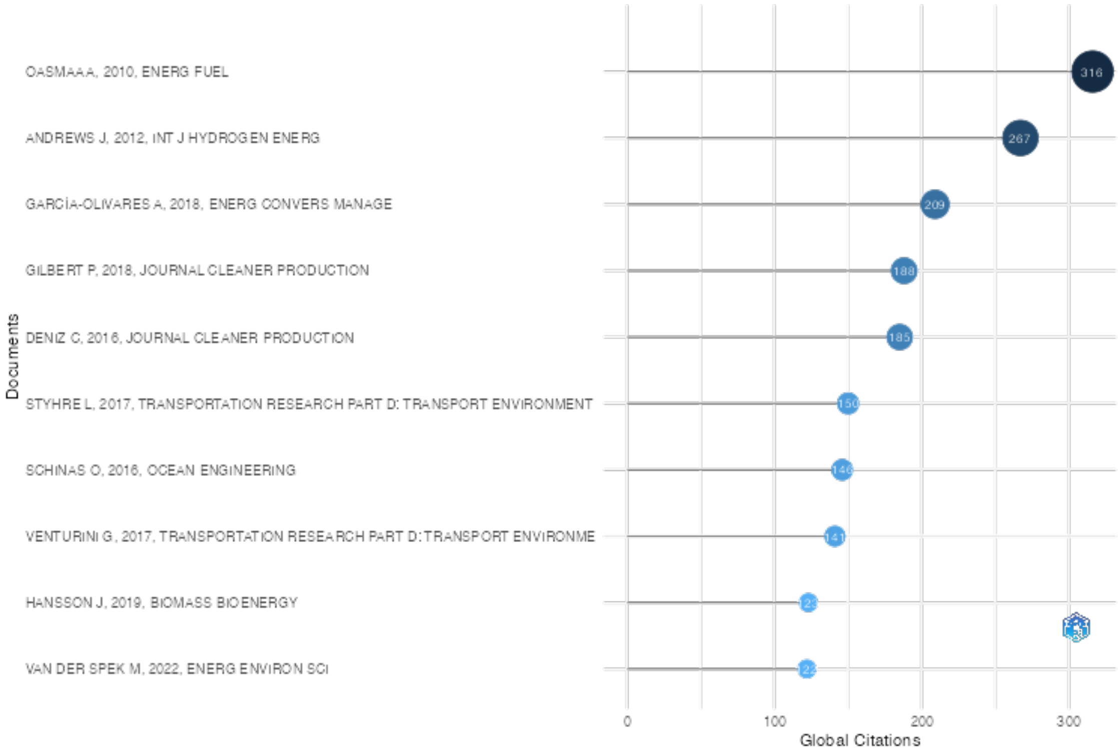

Figure 16: Most globally cited documents.

Starting with Oasmaa et al. (2010) in Energy Fuels, the study explores the production of fast pyrolysis bio-oil from wood and agricultural residues, highlighting the benefits and challenges of different feedstocks and the economic viability of integrated pyrolysis systems. This focus on bio-oil production transitions to the broader integration of hydrogen into the energy economy, as Andrews & Shabani (2012) discussed in the International Journal of Hydrogen Energy. They propose hydrogen as a complementary energy source alongside electricity and batteries, emphasizing its role in long-term storage and transportation.

Building on the theme of renewable energy, García-Olivares et al. (2018), in Energy Conversion and Management, review the technological and energetic requirements for transitioning to a 100% renewable energy system. Their findings on the efficiency gains in road transport and the increased energy demands for shipping and air transport provide a foundation for Gilbert et al. (2018) in the Journal of Cleaner Production. This study conducts a life-cycle assessment of alternative shipping fuels, identifying hydrogen and bio-derived fuels as potential solutions if production processes are decarbonized.

The economic and environmental performance of alternative marine fuels is further examined by Deniz & Zincir (2016) in the Journal of Cleaner Production. Using the Analytic Hierarchy Process, they find LNG the most suitable alternative, balancing environmental benefits and economic feasibility. This discussion of LNG is expanded by Styhre et al. (2017) in Transportation Research Part D, who analyze greenhouse gas emissions from ships in ports and recommend additional measures like on-shore power supply to reduce emissions.

Schinas & Butler (2016), in Ocean Engineering, explore LNG-fueled ships' feasibility and commercial considerations, discussing regulatory frameworks and market incentives. The operational aspects of maritime logistics are further explored by Venturini et al. (2017) in Transportation Research Part D, who address the Berth Allocation Problem with speed optimization and emission considerations, highlighting the importance of cooperation between shipping lines and terminal operators.

Hansson et al. (2019) in Biomass Bioenergy assess alternative marine fuels using multi-criteria decision analysis, finding that economic criteria favour fossil-based options like LNG and HFO, while environmental criteria favour renewable hydrogen and methanol. Finally, van der Spek et al. (2022) in Energy & Environmental Science provide a comprehensive analysis of the hydrogen economy's potential to achieve net-zero CO2 emissions in Europe, emphasizing the need for robust infrastructure and supportive policies.

Over the years, the maritime industry has witnessed an evolving focus and trends on various research topics, reflecting technological advancements and increasing environmental concerns, as shown in Figure 17. This chronological perspective outlines the shifting priorities and emerging trends in maritime research.

In the early years (2013-2016), a focus on **engine and design** prevailed. This period saw significant efforts to innovate and improve ship designs to meet evolving regulatory and operational requirements. By 2015, research on **engine** performance became prominent, indicating a growing interest in optimizing engine efficiency and performance for maritime applications.

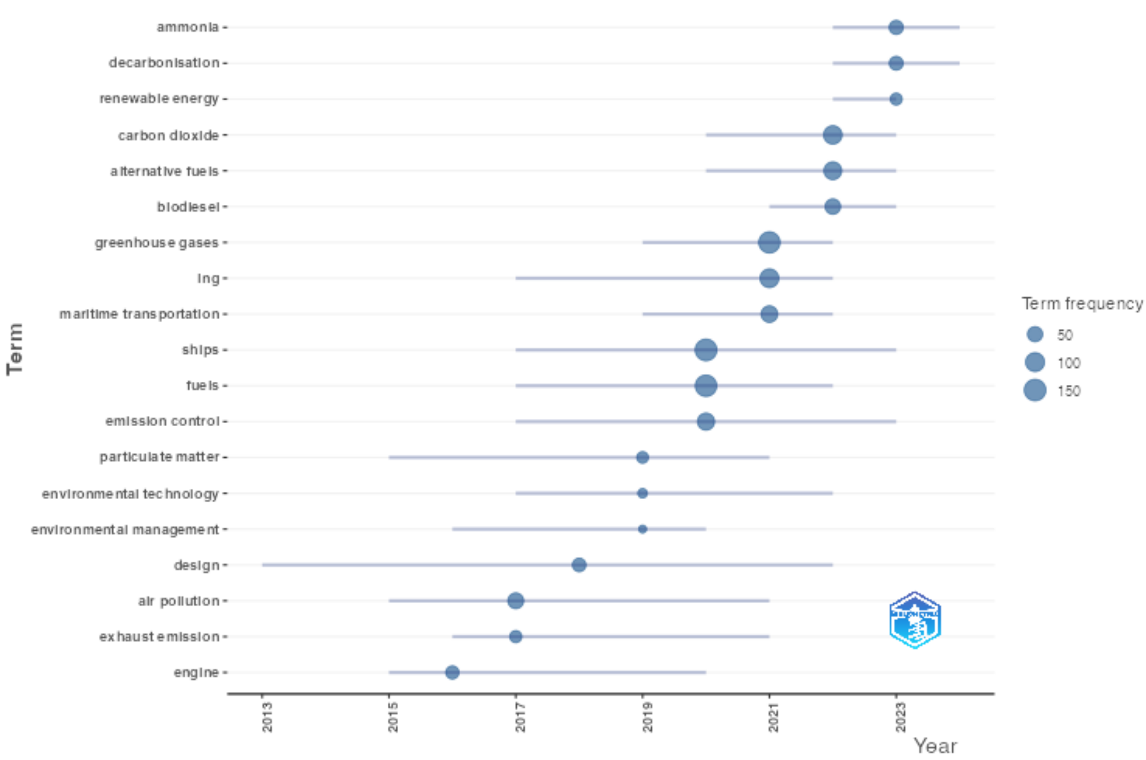

Figure 17: Trend topics of the scoping review.

From 2015 through 2017, there was a heightened awareness of **air pollution** caused by maritime activities. This concern led to increased research on **exhaust emissions** from ships, with significant attention paid to understanding and mitigating these emissions by 2016. These efforts aimed to address the adverse environmental impacts of shipping and were crucial in paving the way for developing more sustainable maritime practices.

Simultaneously, from 2015 onwards, **particulate matter** emissions became a focal point, highlighting the need to improve air quality by reducing emissions. By 2017, the interest in **environmental technology** began to rise, reflecting advancements in technologies **designed** to minimize the **environmental** footprint of maritime operations. This period marked the beginning of integrating innovative solutions to combat pollution effectively.

From 2017, **emission control technologie**s gained significant traction as international regulations demanded stricter compliance with emission reduction targets. Concurrently, research on **greenhouse gases** intensified, particularly from

2019 to 2022, driven by global commitments to mitigate climate change. These efforts underscored the industry's dedication to reducing its contribution to global greenhouse gas emissions through technological and regulatory measures.

The Rise of LNG and sustainable fuels occurred between 2017-2022. **LNG** emerged as a promising alternative fuel, with research peaking between 2017 and 2022. The exploration of **fuels** remained a dominant topic, highlighting the industry's ongoing quest for sustainable fuel options to power maritime vessels. The discussions around ships also persisted, reflecting a continuous effort to **optimize ship** technologies alongside **fuel innovations**.

Around 2020, the focus shifted significantly towards reducing **carbon dioxide emissions**. This shift was coupled with an increasing interest in **alternative fuels** from 2020 to 2023, showcasing the industry's urgency to find **low-carbon and carbon-neutral fuel** options to meet stringent climate goals, and this period marked a crucial phase in exploring diverse fuel types to support sustainable maritime operations.

From 2021, **biodiesel** became a **viable alternative fuel**, demonstrating its potential in reducing emissions. The interest in **ammonia** and **decarbonisation** peaked from 2022 to 2024, reflecting the industry's shift towards **more radical solutions** for achieving zero emissions. Research on **renewable energy** also surged during 2022-2023, underscoring the growing interest in integrating renewable energy sources into **maritime operations.**

Throughout these years, **maritime transportation** remained a consistent topic of study from 2019 to 2022. This focus highlighted the industry's efforts to optimize logistics and reduce environmental impacts. The comprehensive approach to addressing environmental challenges involved exploring innovative solutions in **ship design**, **engine** performance, and **fuel technologies**, paving the way for a more sustainable future in maritime transportation.

An analysis of the co-occurrence of words was undertaken, and the results are shown in Figure 18. The red cluster, "Environmental Emissions and Energy Systems", comprises the key topics of environmental emissions, combustion, energy, system, performance, technologies, and energy management. This cluster focuses on the intersection of energy systems and environmental emissions. The central theme is understanding how different energy systems and technologies impact emissions. Including keywords such as "combustion" and "performance" suggests a focus on improving the efficiency and reducing the emissions of combustion processes. “Energy management” implies strategies for optimizing energy use to minimize environmental impact.

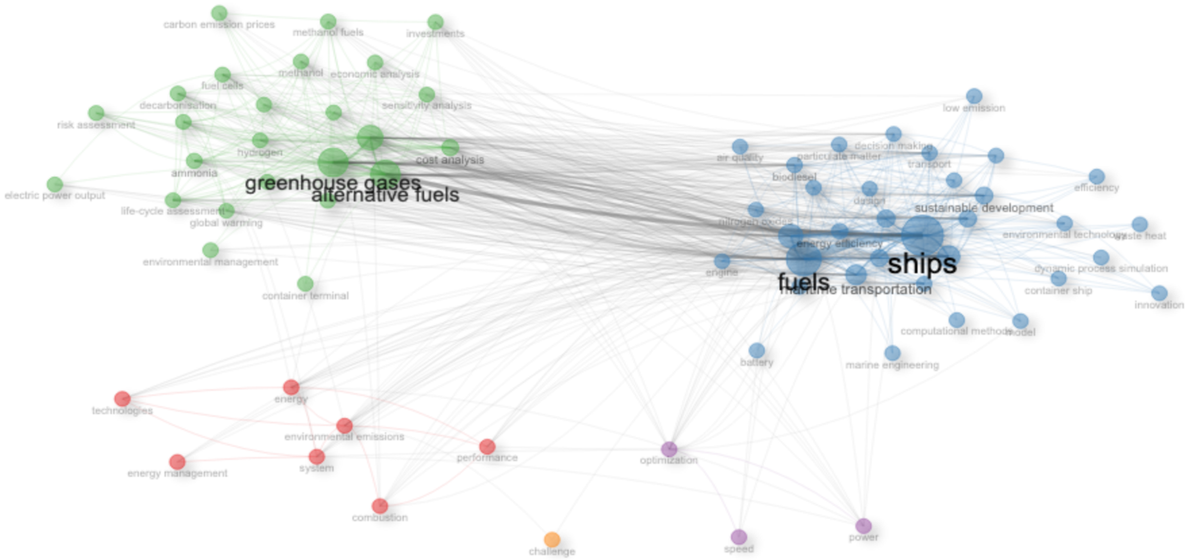

Figure 18: Co-occurrence of keywords’ network.

The blue cluster, “Maritime Transportation and Sustainable Fuels,” comprises the following key topics: ships, fuels, LNG, emission control, maritime transportation, air pollution, sustainable development, biodiesel, energy efficiency, shipping, climate change policies, decision-making, ship propulsion, diesel engine, IMO, nitrogen oxides, particulate matter, design, engine, air quality, marine engineering, battery, efficiency, environmental technology, waste heat, computational methods, container ship, dynamic process simulation, innovation, low emission. This cluster is centred on maritime transportation and the shift towards sustainable fuels and technologies. It includes various topics, from specific fuels, e.g. LNG and biodiesel, to overarching themes like sustainable development and climate change policies. The high betweenness of “ships” and “fuels” highlights the centrality of these topics in discussions about reducing maritime emissions. “Emission control,” “energy efficiency,” and “sustainable development” indicate a strong focus on regulatory compliance and innovative solutions to mitigate the environmental impact of shipping.

The green cluster “Alternative Fuels and Carbon Management” comprises the key topics: greenhouse gases, alternative fuels, carbon dioxide, hydrogen, cost analysis, ammonia, life-cycle assessment, decarbonisation, fuel cells, environmental impact, energy demand, renewable energy, cost-effectiveness, maritime industry, risk assessment, methanol, global warming, economic analysis, sensitivity analysis. This cluster deals with exploring and evaluating alternative fuels and their role in carbon management. Keywords like “greenhouse gases,” “alternative fuels,” and “carbon dioxide” suggest a focus on reducing emissions by innovative fuel options such as hydrogen, ammonia, and methanol. “Life-cycle assessment” and “cost analysis” suggest comprehensive evaluations of these fuels’ environmental and economic impacts.

The purple cluster, “Optimization and Power Management”, conveys the following key topics: optimization, power, and speed. This cluster emphasizes the technical and operational optimization of maritime systems. “Optimization” and “power” indicate a focus on improving the performance and efficiency of maritime operations. The presence of “speed” suggests that optimizing vessel speed for fuel efficiency and reduced emissions might be a key area of research within this cluster.

Finally, the orange cluster, “Challenges in Maritime Sustainability”, conveys only one edge: challenge. Although this cluster contains only one keyword, “challenge,” it represents the difficulties and barriers in achieving maritime sustainability. It may encompass the industry’s technical, economic, regulatory, and operational challenges in transitioning to greener practices and technologies.

The factorial analysis results provide insights into the positioning of key topics within the identified dimensions (Dim1 and Dim2) and their respective clusters, as shown in Figure 19.

The cluster “Maritime emissions and fuel alternatives” primarily focuses on the environmental impacts of maritime transportation and the adoption of various low-carbon fuels. The keywords strongly emphasise understanding and mitigating greenhouse gas emissions and exploring alternative fuel options like LNG, biodiesel, and renewable energy. The presence of terms like “life cycle assessment” and “cost analysis” suggests a comprehensive approach to evaluating these alternatives’ economic and environmental benefits. This cluster also highlights the regulatory aspects (e.g., IMO regulations) and the importance of economic considerations in adopting sustainable practices.

The cluster “Policy, decision making, and stakeholder involvement” focuses on the policy and decision-making aspects of adopting low-carbon fuels in the maritime industry. The keywords reflect the involvement of various stakeholders and the importance of making informed decisions based on environmental impacts and energy demand. Terms like “sustainable development” and “environmental technology” highlight the industry’s broader goals of sustainability and innovation. This cluster underscores the need for effective decision-making frameworks considering environmental and economic factors.

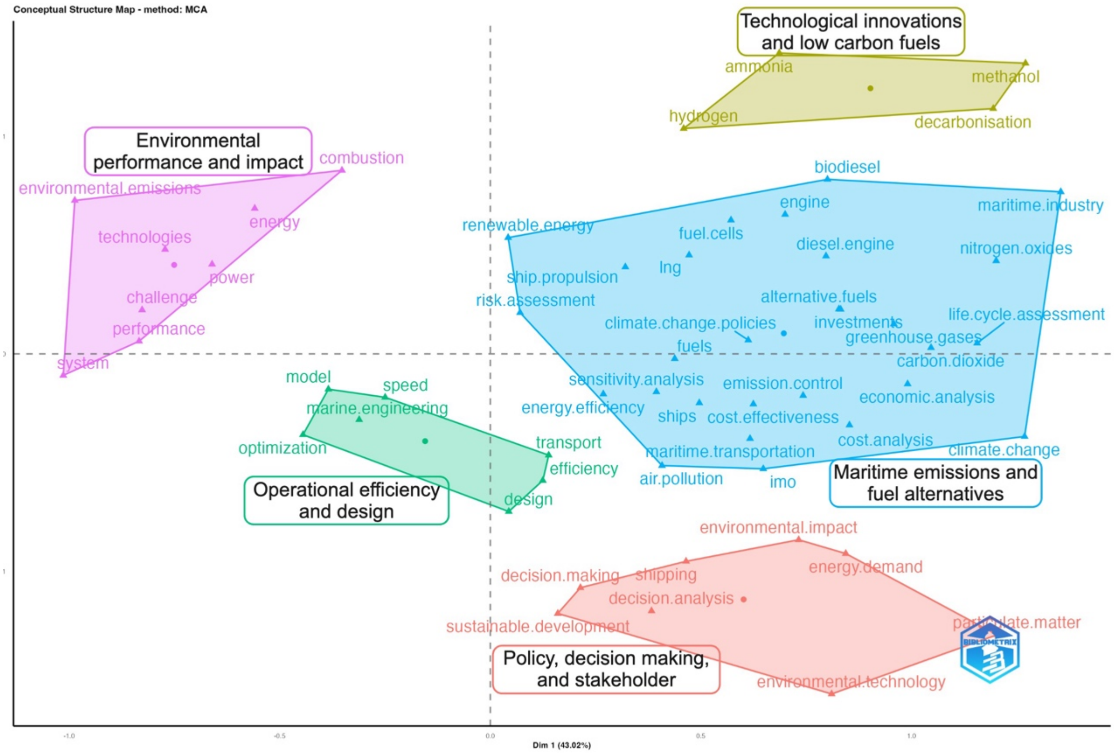

Figure 19: Conceptual structure map.

The cluster “Technological innovations and low-carbon fuels” emphasizes the technological advancements and specific low-carbon fuels explored in the maritime industry. The keywords “hydrogen”, “ammonia”, “decarbonization”, and “methanol” indicate a focus on cutting-edge technologies and innovative fuel options that have the potential to reduce carbon emissions significantly in the long run. This cluster highlights the ongoing research and development efforts aimed at finding sustainable and effective fuel alternatives for maritime operations.

The cluster “Operational Efficiency and Design” is centred around the operational aspects of maritime transportation, including optimization, design, and efficiency. The keywords suggest a focus on improving the performance and efficiency of maritime operations through better design and optimization techniques. Terms like “marine engineering” and “efficiency” indicate the technical and engineering challenges in enhancing ships' operational performance. This cluster highlights the importance of optimizing existing systems for better environment and economic outcomes.

The last cluster, "Environmental performance and impact", addresses maritime operations' environmental performance and impact. The keywords focus on understanding and improving the environmental performance of ships, particularly in terms of emissions and energy use. Terms like "environmental emissions", "combustion", and "energy" highlight the technical challenges involved in reducing emissions and improving energy efficiency. This cluster also includes keywords related to the performance and power of maritime systems, indicating an interest in enhancing the overall environmental performance of maritime operations through technological and operational improvements.

4.1.3 Results of the descriptive analysis of the scoping review

This section of the scoping review synthesizes findings from 90 articles, focusing on the industry's stakeholders, enablers, barriers, alternative fuels, criteria, decision-making processes, and practical recommendations for adopting low-carbon fuels.

4.1.3.1 Stakeholders and Institutional Pressure

Adopting low-carbon fuels in the maritime industry is influenced by various institutional pressures that shape decision-making and implementation strategies (Cajaiba-Santana et al., 2020; Kuo et al., 2022; Oliver, 1991; Peng, 2003). DiMaggio & Powell (1983) classify these pressures into three main types: coercive, normative, and mimetic. Table 7 categorizes the specific pressures and stakeholders associated with each type, providing a structured understanding of how different forces drive the transition towards sustainable maritime practices.

This categorization highlights how regulatory frameworks and economic incentives (coercive pressures) drive compliance and adoption of low-carbon technologies, while standards of technological feasibility, operational guidelines, and sustainability goals (normative pressures) ensure robust and reliable implementation. Simultaneously, market trends, best practices, and collaborative efforts (mimetic pressures) influence stakeholders to adopt innovative and efficient solutions. Understanding these dynamics is crucial for developing effective strategies that align with global sustainability objectives and regulatory requirements.

Table 7: Classification of Institutional pressures and stakeholders in the adoption of low-carbon fuels in maritime transportation.

	Types of Institutional Pressure (DiMaggio & Powell, 1983)		
	Coercive	**Normative**	**Mimetic**
Pressure typification	Compliance with international and national regulations, emission reduction targets, economic incentives and subsidies, environmental regulations, and regulatory mechanisms.	Technological maturity and feasibility, operational feasibility, environmental and sustainability goals, institutional support and governance, safety and reliability concerns, risk assessment and management, sustainable agricultural practices, climate change mitigation, and environmental regulations compliance.	Market competitiveness, adoption of best practices, stakeholder collaboration, customer demand and market trends, social acceptance, and environmental consciousness.
Stakeholders	Policymakers and regulatory bodies (e.g., IMO, European Union, National and local government agencies, environmental regulatory bodies, port and terminal authorities, local agencies).	Universities, researchers and academic institutions, international classification societies (e.g., Lloyd's Register, Croatian Register of Shipping), industry associations (e.g., European Community Shipowners' Associations), urban Harbours Institute (UHI), maritime sector associations (e.g., Great Lakes maritime research institute) and financial institutions.	Environmental and non-governmental organizations (e.g., Green Peace, WWF, civil society), ship operators and owners, engine manufacturers (e.g., MAN Diesel and turbo, Wartsila), fuel and bunker suppliers and marine fuel producers, shipbuilders and designers, logistics companies, technology developers (e.g., Clean Energy Research Laboratory (CERL), Public and Private Partnerships, consumers and end users (e.g., passengers, coastal populations and general public), port operators and multilateral development banks.

4.1.3.2 Issues, models for decision-making, alternatives and main criteria

The maritime industry is undergoing significant transformations to address environmental concerns and comply with regulatory requirements. The industry has been actively exploring various strategies to reduce emissions, improve fuel efficiency, and integrate sustainable technologies. Table 8 categorizes articles related to these efforts, providing insights into the focus areas, decision-making models employed, and the alternative fuels assessed. This categorization aims to offer a structured and synthesized view of the current research and its implications for sustainable maritime operations.

Effective decision-making processes are critical in this transition, as they enable stakeholders to evaluate and select appropriate technologies and strategies that align with both regulatory requirements and economic feasibility. The decision-making models vary in their approaches and complexities. For instance, AHP and MCDM focus on evaluating multiple criteria simultaneously, while optimization models aim to find the most efficient solution. Scenario analysis provides a flexible framework to assess various future possibilities, whereas legal and regulatory frameworks ensure compliance with existing laws and policies. Simulation models and agent-based modelling offer dynamic and interactive ways to predict and assess the performance of technologies.

The decision-making models and criteria are interconnected and often dependent on one another. For example, regulatory compliance drives the need for technologies that reduce emissions, which in turn affects cost-effectiveness and operational feasibility. Economic feasibility and technical readiness are crucial for the adoption of new technologies, while social acceptance can influence regulatory frameworks and market-based approaches.

The findings highlight the complexity of decision-making in the maritime sector's transition to low-carbon fuels. Effective decision-making requires a holistic approach that considers multiple criteria and the interdependencies between them. Stakeholders must collaborate to balance environmental, economic, and technical aspects to achieve sustainable outcomes. The adoption of comprehensive decision-making models can help navigate the challenges and uncertainties associated with low-carbon fuel technologies, ensuring a smoother transition and greater alignment with global emission reduction goals.

Table 8: Categorization of articles on the maritime industry and low-carbon fuels, grouped by focus areas, decision-making models, and fuels.

Citations	Description	Models and tools	Fuels
Brahim et al. (2019), Cheliotis et al. (2021), Claremar et al. (2017), Corbett & Winebrake (2008), Cortez et al. (2021), Deniz & Zincir (2016), Farrell & Glick (2000), Hampp et al. (2023), Hong et al. (2023), Lagemann et al. (2023), Martínez-López et al. (2018), Panoutsou et al. (2022), Pettit et al. (2018), Simmer et al. (2014), Xing et al. (2021), Zhou et al. (2021)	**Environmental impact and emissions reduction:** Articles focusing on reducing the environmental impact of maritime operations, specifically targeting emissions reductions using alternative fuels, technologies, and operational strategies.	Optimization models	Hydrogen, methanol, ammonia, LNG, biofuels.
		Scenario analysis	Heavy fuel oil (HFO), marine gas oil (MGO).
		Regulatory frameworks and market-based approaches	Natural gas.
		Reliability assessment tools	Ammonia, hydrogen, natural gas, methanol.
Andric et al. (2019), Broman (2012), Chica et al. (2023), Chua et al. (2018), Gumus (2024), Lin (2013), Llamas & Eriksson (2019), Oliveira et al. (2022), Rawlinson et al. (2023), J. Ren & Lützen (2015), J. Z. Ren & Liang (2017), Stewart & Wolosz (2015), Strantzali et al. (2023), Voyer & van Leeuwen (2019)	**Technological innovations and fuel efficiency:** Articles focusing on technological advancements and innovations aimed at improving fuel efficiency and integrating new propulsion systems in the maritime industry.	Multi-criteria decision-making (MCDM)	Methanol, hydrogen, LNG, bio-LNG, e-LNG, fossil methanol, bio-methanol, ammonia.
		Optimization-based strategies	Marine diesel oil (MDO), batteries.
		Simulation models	LNG, marine gas oil (MGO).
		Agent-based modelling	Wind propulsion technologies (WPTS).
Dade & Witzig (1974), Hoang et al. (2021), Khondaker et al. (2016), Liu et al. (2020), Stalmokaitė & Yliskylä-Peuralahti (2019), Q. Wang et al. (2023)	**Policy and regulatory compliance:** Articles addressing the implications of policy and regulatory frameworks on maritime fuel choices and emissions management, focusing on compliance with international and regional standards.	International mitigation governance	Marine diesel oil (MDO), LNG, biofuels, nuclear energy, solar and wind energy, and fuel cells.
		Multi-level perspective (MLP)	LNG, methanol, low-sulphur fuel, heavy fuel oil.
		Legal analysis	LNG, ammonia, biofuels, hydrogen, nuclear, electricity, methanol.
		Lifecycle assessment (LCA)	Fast pyrolysis bio-oil (FPBO), biodiesel, biogas, bio-methanol.
Deniz & Zincir (2016), García-Olivares et al. (2018), Hampp et al. (2023), Han et al.	**Economic and operational feasibility:** Articles evaluating	Optimization models	Hydrogen, methanol, ammonia, LNG, biofuels.

Citations	Description	Models and tools	Fuels
(2023), Lagemann et al. (2023), Liu et al. (2020), Martínez-López et al. (2018), Oliveira et al. (2022), Shankar et al. (2022), Simmer et al. (2014), Stalmokaitė & Yliskylä-Peuralahti (2019), Voyer & van Leeuwen (2019), Zhou et al. (2021)	the economic and operational feasibility of alternative fuels and technologies, considering factors such as cost, performance, and implementation challenges.	Economic assessment models	LNG, marine gas oil (MGO).
		Marginal abatement cost curves (MACC)	Alternative fuels with and without carbons.
		Two-stage stochastic programming	Bunker fuel.

Table 9 presents a comprehensive summary of the decision-making processes and the associated criteria relevant to the adoption of low-carbon fuels in the maritime sector. The table categorizes the decision-making models into specific groups, such as the multi-criteria decision making (MCDM), Optimization Models, and Lifecycle Assessment (LCA), among others. It associates each model with the criteria prioritized by stakeholders. This structured presentation aims to provide a clear understanding of the various factors influencing decision-making in the transition towards low-carbon maritime fuels.

Table 9: Decision-making processes and criteria taxonomy for alternative fuel adoption.

Decision-Making Process	**Criteria**
Optimization Models	(E) - Total system costs, Socio-economic costs, Cost of ownership, Retrofit costs, Lost opportunity costs, Fuel costs, Minimization of operational costs, (T) - Fuel efficiency, Power performance, Optimization of charging/refuelling strategies, (EN) - Global warming potential (GWP), Emissions reduction, Compliance with emissions regulations, (O) - Long-term investment viability, Asset health.
Scenario Analysis	(E) - Cost Savings, (EN) - Emission Reduction, (O) - Fuel Consumption.
Regulatory Frameworks and Market-Based Approaches	(EN) - Emissions reductions, Emission Reduction Potential, (E) - Cost-effectiveness, (R) - Regulatory compliance, (O) - Operational feasibility, Feasibility, Impact on Trade.
Reliability Assessment Tools	(EN) - Environmental impact, (T) - Fuel availability, Energy efficiency, (S) – Safety, (E) - Cost (operational and investment), (R) - Compatibility with international rules.
Multi-Criteria Decision-Making (MCDM)	(EN) - Environmental impact (GHG emissions), (E) - Economic feasibility (costs of fuel, maintenance, investment), Commercial effects, (T) - Technical readiness, Energy efficiency, Power capacity, Sensitivity to fuel impurities, technical maturity, Engine performance, (S) - Social acceptance, Safety, (R) - Compliance with regulations, (O) - Global availability, Bunker capability, Durability, Adaptability to existing ships, Effect on engine components.
Simulation Models	(T) - NOx emission reduction, Fuel efficiency (specific fuel oil consumption), fuel consumption, Cargo carrying capacity, Construction cost, Engine performance, (E) - Cost of engine testing, Profitability, (EN) - Emission per freight unit.
Agent-Based Modelling	(E) - Economic feasibility, Fuel savings, Installation and maintenance costs, (S) - Awareness of technology, Policy incentives.
International Mitigation Governance	(E) - Cost-effectiveness, (T) - Technological and operational feasibility (EN) - Emission Reduction Potential, (R) - Compliance with Regulations, (O) - Impact on Trade.

Decision-Making Process	**Criteria**
Multi-Level Perspective (MLP)	(R) - Compliance with regulatory standards, (E) - Cost of compliance (T) - Technological feasibility, (EN) - Environmental impact, (M) - Market competitiveness, Customer demand, corporate image.
Legal Analysis	(R) - Legal standards, (S) - Safety regulations, (C) - International cooperation.
Lifecycle Assessment (LCA)	(E) - Environmental sustainability, Climate impact reduction, Environmental benefits, (T) - Fuel quality, Technological feasibility, (E) - Economic viability, (O) – Feasibility.
Economic Assessment Models	(E) - Economic profitability, Investment costs, Operational costs, Fuel price, Lifecycle costs
Marginal Abatement Cost Curves (MACC)	(E) - MAC values, Implementation rates, Economic feasibility of measures, (EN) - Mitigation potentials.
Two-Stage Stochastic Programming	(E) - Minimizing ship deployment cost, Minimizing expected container vessel inventory cost, Minimizing expected bunkering cost

Note: The taxonomy categories are: (T) – Technical, (E) – Economic, (EN) – Environmental, (R) – Regulatory, (S) - Safety and Reliability, (O) - Operational and Feasibility, (S) - Social and Acceptance, (C) - Collaborative and Organizational, (M) - Market and Demand.

As global awareness of environmental issues intensifies, there is a pressing need for the sector to adopt low-carbon fuels and technologies. This transition, however, encounters several challenges and barriers that need to be addressed. In this section, the challenges identified through a scoping review of the literature are presented, highlighting the technological, economic, regulatory, operational, infrastructure, market, and environmental hurdles that impede progress.

Despite these significant challenges, there are numerous enablers and positive influences that can facilitate the transition to low-carbon fuels. From technological advancements and potential zero carbon or carbon-neutral fuels to supportive regulatory frameworks and economic incentives, the maritime industry has a range of tools and opportunities at its disposal. Collaborative efforts, environmental and operational benefits, supportive infrastructures, and favourable market trends further underscore the potential for a successful shift towards sustainable practices.

It is important to note that these challenges and enablers can also vary significantly depending on the specific alternative fuel under study. Each type of fuel presents its own unique set of difficulties and practicalities, which must be considered when planning and implementing sustainable maritime solutions.

4.1.3.3 The alternative fuels assessed

The analysis of alternative fuels in the maritime industry over the years reveals a growing interest in and assessment of various fuel types, reflecting the sector's efforts to transition towards more sustainable energy sources, as shown in Figure 20. This data shows not only the diversity of fuels being considered but also an increasing number of studies examining these alternatives over time.

One of the notable trends is the variety of fuels assessed in the studies. This diversity includes ammonia, biodiesel, diesel, electric and hybrid systems, heavy fuel oil (HFO), hydrogen, liquefied natural gas (LNG), liquefied petroleum gas (LPG), low sulphur fuel oil (LSFO), marine diesel oil (MDO), marine gas oil (MGO), methane, methanol, and even nuclear energy. This broad range of fuels indicates a significant exploration of potential solutions to reduce the maritime sector's carbon footprint.

The data also highlights a growing number of fuels being assessed over the years. Initially, only a few fuels, such as biodiesel and MDO, were considered. Still, as the years progressed, alternatives like hydrogen, LNG, and methanol started to appear more frequently in the studies. This increase is particularly evident from 2016 onwards, reflecting a heightened focus on finding viable low-carbon fuels.

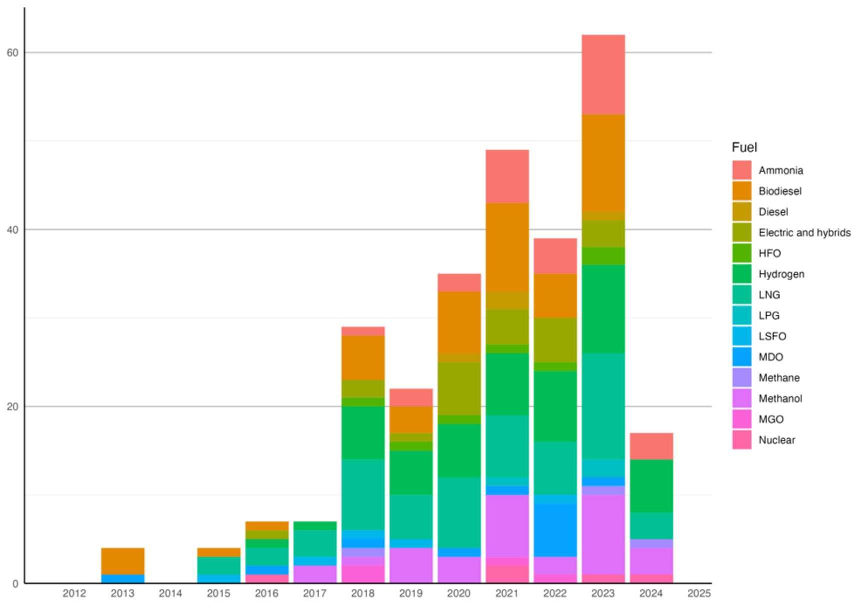

Figure 20: Distribution of alternative fuels assessed in maritime industry studies by year (2013-2024).
Note: The chart illustrates the growing variety and frequency of alternative fuels evaluated over the years, highlighting a significant increase in the number of studies from 2016 onwards. Hydrogen, LNG, and biodiesel emerge as the most recurrent fuels, reflecting the industry's focus on these potential solutions for reducing carbon emissions.

Among the various fuels, some are more recurrent in the studies than others. For example, hydrogen, LNG, and biodiesel are frequently assessed, indicating their potential viability and the industry's interest in these options. Hydrogen, in particular, shows a steady increase in studies, peaking at ten assessments in 2023. Similarly, LNG has seen a substantial number of studies, reaching a high of 12 in 2023. Biodiesel also shows significant attention, especially in the years 2021 and 2023, with 10 and 11 studies, respectively.

Electric and hybrid systems, while less frequent than hydrogen and LNG, also show a consistent presence in the studies, reflecting the growing interest in electrification as a means to decarbonize maritime operations. Methanol, another fuel gaining traction, shows a notable increase in assessments, especially in recent years, with a peak of 9 studies in 2023.

Traditional fuels like diesel and HFO still appear in the studies, albeit less frequently, indicating a continued evaluation of these fuels' roles and impacts in the transition towards cleaner alternatives. These fuels appear in studies as baselines for comparison with the alternatives and also for evaluating their performance with carbon capture devices and scrubbers. Additionally, more unconventional options such as nuclear energy, though assessed less frequently, demonstrate the industry's openness to exploring a wide range of possibilities.

The data from industry sources reveals a decade of trends in the maritime industry's adoption of alternative fuels, revealing significant shifts in preferences and technologies (Atchison, 2024). Historically, LNG has been the dominant fuel choice, reflecting its maturity and established infrastructure. However, there is a noticeable decline in LNG contracts beginning in 2022, suggesting a pivot towards more diverse fuel options or a potential saturation in the LNG market (Lepic, 2024). Concurrently, there has been a notable increase in contracts for vessels capable of using methanol, which surged from representing just 1% of total orders in 2020 to 7% by 2024. This increase highlights methanol's growing appeal, possibly due to its lower retrofitting costs and ease of integration into existing fuel systems (Wold, 2024).

Emerging trends in the adoption of other fuels such as biofuels, hydrogen, ammonia, and ethanol also stand out (Atchison, 2024). The introduction and steady increase in contracts for ammonia and ethanol indicate their rising prominence and the industry's interest in exploring zero-emission solutions. Additionally, biofuels and hydrogen are gaining traction, as evidenced by the growing number of contracts since the late 2010s. The percentage of contracts for alternative fuel capable vessels has grown impressively, reaching 25% of total orders by YTD 2024, signalling a strong shift towards alternative fuels in response to regulatory demands and the global push for reduced environmental impact in maritime operations (Atchison, 2024).

The increasing number of studies assessing these various fuels underscores the maritime industry's commitment to identifying and implementing alternative fuels. This commitment is driven by the need to meet regulatory requirements, reduce greenhouse gas emissions, and enhance sustainability. The stacked chart illustrating the distribution of fuel types by year will visually represent these trends, highlighting the increasing variety and number of alternative fuels being considered over time.

4.1.3.4 Challenges and barriers

The following texts provide a detailed examination of the identified barriers, offering a comprehensive overview of the current landscape of the maritime industry.

4.1.3.4.1 Technological Challenges

The maritime industry faces significant technological challenges in adopting low-carbon fuels. One of the primary issues is the limited long-term prospects for carbon-containing fossil fuels onboard ships due to the difficulties associated with carbon capture. Hydrogen suffers from low volumetric energy density, making its storage and transportation problematic. Ammonia, another potential fuel, raises safety, storage, and infrastructure concerns. Methanol produced from renewable sources encounters production costs and infrastructure issues. Designing and operating low-emission ships and retrofitting existing vessels to accommodate new technologies present substantial hurdles. Moreover, there is a need for the development of accurate and economical methods for measuring emissions. The technological immaturity and complexity, coupled with the limited availability of renewable energy sources and issues of scalability, further complicate the transition to low-carbon fuels.

4.1.3.4.2 Economic Barriers

High initial costs for infrastructure development and retrofitting existing vessels pose significant economic barriers. The process of refining lower-sulfur fuels increases energy requirements and CO_2 emissions, adding to the economic burden. Biofuels, while being a cleaner alternative, come with high production and feedstock costs. The overall investment and maintenance costs associated with alternative fuels and technologies are considerable. Additionally, the price volatility of fuels like LNG can deter investment. Market resistance due to economic concerns and the high costs of alternative fuels and technologies further hinder the widespread adoption of low-carbon options.

4.1.3.4.3 Regulatory Hurdles

Navigating the regulatory landscape is a major challenge for the maritime industry. Obtaining regulatory approval for new technologies can be a lengthy and complex process. Integrating new fuels and technologies into existing emissions trading programs poses additional difficulties. Compliance with varying regulatory frameworks and policies across different jurisdictions adds to the complexity. Fragmented governance and the lack of international cooperation on maritime emissions create further obstacles. Regulatory and policy uncertainties can also hinder investment and innovation in low-carbon technologies.

4.1.3.4.4 Operational Concerns

Operational challenges include ensuring safe and efficient refuelling operations and managing fuel storage and handling issues. The space limitations on existing ships can make it difficult to accommodate new technologies. Operating in varying conditions, such as the Arctic, introduces additional complexities. The integration of hybrid power sources and the complexity of power management and real-time optimization are also significant concerns. These operational challenges require substantial changes to existing practices and systems.

4.1.3.4.5 Infrastructure and Supply Chain Limitations

The limited infrastructure for alternative fuels is a critical barrier. Ensuring a reliable supply chain for new fuels, such as hydrogen and ammonia, presents considerable challenges. Significant infrastructure development is needed to support the widespread use of these fuels. Storage and transportation issues further complicate the supply chain dynamics, necessitating substantial investments in new facilities and technologies.

4.1.3.4.6 Market and Social Barriers

Market inertia and resistance to change are significant barriers to the adoption of low-carbon fuels. Social acceptance issues and resistance to behavioural changes among stakeholders can slow down the transition. Competitive pressures in the shipping industry make it difficult for companies to adopt new technologies and practices that might increase operational costs or require significant changes to existing systems.

4.1.3.4.7 Environmental and Safety Concerns

Safety concerns with the handling and storage of new fuels, such as hydrogen and ammonia, are significant. There are also environmental risks associated with the cultivation of biofuels on contaminated lands. Some alternative fuels can have negative effects on engine components, and certain fuels may produce high emissions at partial loads, undermining their environmental benefits.

4.1.3.4.8 Technical and Economic Feasibility

The high costs of testing and research for new technologies and fuels are considerable barriers. Technological readiness and the need for adaptation to maritime applications require significant investments. The high initial investment and operational costs can deter adoption, particularly in the absence of commercial alternatives to liquid petroleum fuels.

4.1.3.5 Enablers and facilitators

The following sections provide an examination of the enablers, offering an overview of the path forward for the maritime industry.

4.1.3.5.1 Technological Advancements

Advancements in technology are crucial for the maritime industry's transition to low-carbon fuels. Significant progress has been made in developing fuel cell power systems, including proton exchange membranes, molten carbonate, and solid oxide fuel cells. More efficient engines and propulsion systems, along with natural gas engine designs, are improving fuel efficiency. Biomimetic technologies are being utilized for drag reduction, and hybrid propulsion systems are becoming more prevalent. Power electronics and control-oriented modelling techniques are enhancing operational efficiency. Advanced design synthesis and analysis techniques, optimization models and algorithms, fuel pre-processing technologies, battery and hybrid systems, and renewable energy systems are all contributing to the industry's ability to adopt low-carbon fuels.

4.1.3.5.2 Potential Zero Carbon or Carbon-Neutral Fuels

The exploration and adoption of potential zero-carbon or carbon-neutral fuels are pivotal for the industry's sustainability efforts. Hydrogen and ammonia are being investigated as promising alternatives due to their low-carbon footprints. Renewable methane and methanol from renewable sources offer potential pathways to decarbonization. Biofuels and biodiesel are increasingly being considered viable alternatives, while LNG and wind-based drives provide additional options for reducing emissions.

4.1.3.5.3 Regulatory and Policy Support

Supportive regulatory and policy frameworks play a vital role in facilitating the transition to low-carbon fuels. Emissions trading programs and regulatory policies favouring low-sulphur fuels are encouraging cleaner practices. International regulations, such as those set by the IMO and the Clydebank Declaration, provide a strong foundation for global compliance. The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) set benchmarks for energy efficiency. Financial incentives from ports and banks, as well as policy support for low-carbon technologies, further incentivize the adoption of sustainable practices.

4.1.3.5.4 Economic Incentives

Economic incentives are essential for overcoming the financial barriers associated with low-carbon fuels. Subsidies and tax incentives can significantly reduce the initial costs of infrastructure development and retrofitting. Market-based mechanisms, such as Emissions Trading Systems (ETS) and Clean Development Mechanism (CDM) projects, provide financial benefits for reducing emissions. Cost savings from improved efficiency, financial incentives for emission reductions, and subsidies for installation costs make low-carbon technologies more attractive. Tax incentives further enhance the economic feasibility of adopting these technologies.

4.1.3.5.5 Collaborative Efforts

Collaboration among various stakeholders is key to advancing the adoption of low-carbon fuels. Public-private partnerships foster innovation and share risks. Collaboration among researchers, industry professionals, policymakers, and ship operators promote knowledge exchange and accelerates technological advancements. International cooperation and agreements ensure a coordinated approach to addressing global challenges. Stakeholder engagement and networking, along with demonstration projects, showcase the viability and benefits of low-carbon technologies.

4.1.3.5.6 Environmental and Operational Benefits

Adopting low-carbon fuels offers significant environmental and operational benefits. These include substantial reductions in air pollutants, which enhance public health and environmental quality. Advanced simulation tools enable optimization of fuel use and operational efficiency. Fuel savings from slow steaming and emission reductions through advanced combustion techniques further support the industry’s sustainability goals. These benefits create a compelling case for the transition to low-carbon fuels.

4.1.3.5.7 Supportive Infrastructures and Market Trends

The development of supportive infrastructures and favourable market trends are critical enablers. The availability of renewable energy sources and infrastructure development for alternative fuels provide the necessary foundation for widespread adoption. Increasing oil prices enhance the competitiveness of alternative fuels. Growing market demand for cleaner transport solutions drives the industry towards sustainable practices. Pilot projects demonstrating the viability of biofuels and other alternatives build confidence and encourage broader adoption.

4.1.3.5.8 Economic and Market Factors

Economic and market factors play a significant role in driving the transition to low-carbon fuels. High fuel prices make fuel savings and efficiency improvements more attractive. Investments from multilateral development banks in renewable technologies support the industry’s efforts. The shared interest of multiple transportation modes creates opportunities for cross-sectoral collaboration and innovation. Potential carbon pricing policies further incentivize the reduction of carbon emissions. Market readiness and the development of necessary infrastructures ensure a smooth transition to low-carbon technologies.

The Sankey diagram presented in Figure 21 illustrates the intricate relationships between enablers, fuel types, and barriers within the maritime industry’s transition to alternative fuels. Each node represents a category: the enablers on the left, the various fuel types in the middle, and the barriers on the right. The links between these nodes indicate the flow and interaction between these elements, with the thickness of the links corresponding to the strength or significance of these relationships.

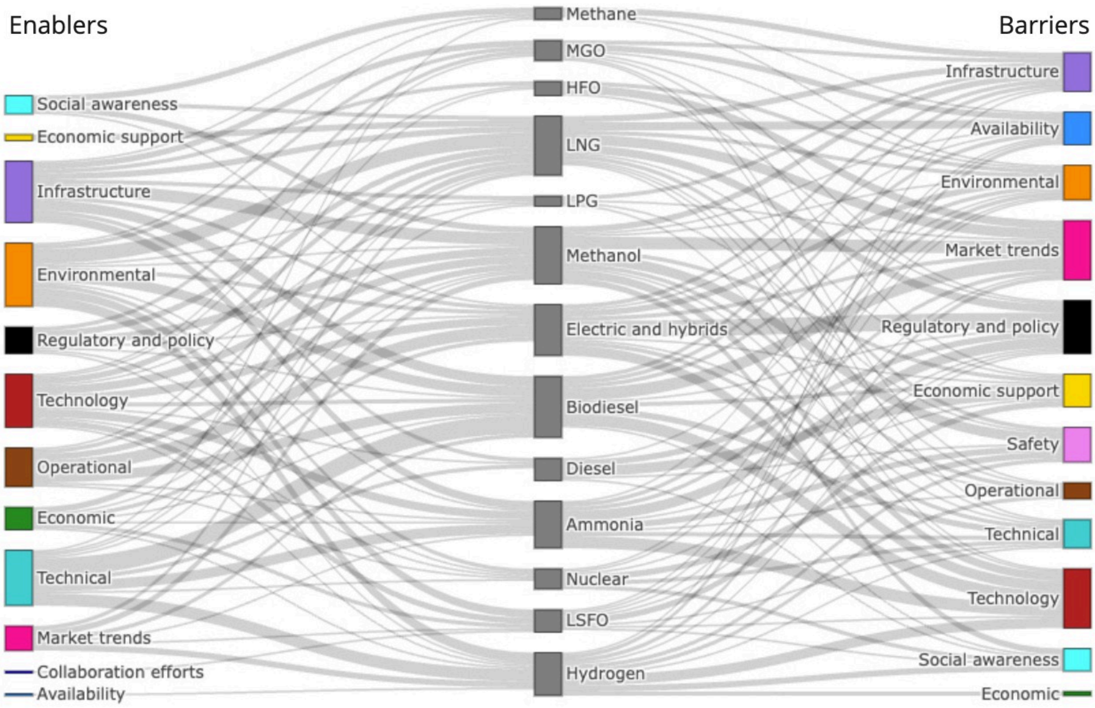

Figure 21: Sankey diagram of enablers, fuel types, and barriers in the maritime industry.

The strength of these relationships was established because of the scoping review, where unique enablers and barriers were counted to reflect their respective connections to each fuel type. The enablers include factors like availability, economic support, regulatory policies, and social awareness, which drive the adoption of different fuel types, such as ammonia, biodiesel, and LNG. These fuels, in turn, face specific barriers, including infrastructure challenges, market trends, and technical limitations. The use of distinct colours and varying levels of transparency helps to differentiate between the various elements and highlight the most significant flows within the system.

The enablers include factors such as availability, economic support, regulatory policies, and social awareness, which drive the adoption of different fuel types, e.g. ammonia, biodiesel, and LNG. These fuels, in turn, face specific barriers, including infrastructure challenges, market trends, and technical limitations. The use of distinct colours and varying levels of transparency helps to differentiate between the various elements and highlight the most significant flows within the system.

By examining, the results indicate that the most significant factors are:

a) Environmental enablers, with a count of 36, are the most influential, highlighting the increasing importance of reducing environmental impacts and complying with environmental regulations by adopting alternative fuels;

b) Technical enablers, with a count of 30, are also critical, reflecting the importance of technical aspects in making alternative fuels viable and efficient for maritime use;
c) infrastructure-related factors counted at 28, play a crucial role. The availability and development of necessary infrastructure for fueling, storage, and maintenance significantly influence the adoption of alternative fuels;
d) operational considerations, with a count of 20, also significantly impact fuel adoption, encompassing operational efficiencies and the practical aspects of integrating new fuels into existing maritime operations;
e) market trends, with a count of 12, are important as well, including the influence of market demand, fuel prices, and industry trends on the adoption of alternative fuels;
f) regulatory and policy factors, with a count of 14, highlight the importance of supportive policies and regulations in promoting the use of alternative fuels;
g) economic support, counted at 11, underscores the need for financial incentives, subsidies, and economic viability in encouraging the transition to alternative fuels.

Among the various barriers to the adoption of alternative fuels in the maritime industry, the results indicate that the most significant factors are:

a) Technical barriers, with a count of 30, are the most prominent, highlighting the critical challenges related to the technical limitations of the fuels and the need for further advancements to make alternative fuels viable for maritime use;
b) Infrastructure-related barriers counted at 26, play a significant role. The lack of necessary infrastructure for fuelling, storage, supply chain, production, and maintenance poses a considerable challenge to the adoption of alternative fuels;
c) environmental barriers, with a count of 25, are also highly influential, reflecting the complexities and potential environmental risks

associated with the use of certain alternative fuels, which can impede their adoption;

d) operational barriers, with a count of 24, are significant as well. These include the practical challenges and inefficiencies that can arise when integrating new fuels into existing maritime operations;
e) technology barriers, with a count of 20, emphasize the need for ongoing technological development and innovation to support the adoption of alternative fuels;
f) regulatory and policy barriers, counted at 18, highlight the challenges posed by the existing regulatory frameworks and policies that may not be supportive of alternative fuels;
g) availability barriers, counted at 14, indicate issues related to the availability and consistent supply of alternative fuels;
h) safety barriers, with a count of 13, indicate concerns about the safety and risks associated with the use of alternative fuels in maritime operations;
i) economic support barriers, also counted at 13, underscore the difficulties in securing the necessary financial incentives and economic viability for adopting alternative fuels;
j) market trends, with a count of 11, reflect the impact of market demand, fuel prices, and industry trends that can hinder the adoption of alternative fuels;
k) social awareness barriers, with a count of 9, highlight the need for increased awareness and acceptance of alternative fuels among stakeholders.

4.1.3.6 Comparative analysis of enablers and barriers

The comparative analysis of enablers and barriers to the adoption of alternative fuels in the maritime industry reveals several critical insights. Environmental enablers, with a count of 36, are the most influential factors driving adoption. However, environmental barriers, counted at 25, also play a major role, indicating a dual focus on leveraging environmental benefits while addressing potential environmental risks.

Technical factors are equally significant as both enablers and barriers, each with a count of 30. This finding reinforces and supports the necessity for ongoing technological innovation and development to overcome existing limitations and make alternative fuels viable. Infrastructure-related enablers (28) and barriers (26) emphasize the importance of developing adequate facilities for fuelling, storage, and maintenance to support alternative fuel adoption.

Operational considerations, with enablers counted at 20 and barriers at 24, significantly impact the integration of new fuels into existing operations. This underscores the need to address practical challenges and inefficiencies. Management, tactical, and operational practices can play a key role in supporting the industry by studying and developing new guidelines to help the industry transition to a sustainable operation regime. Regulatory and policy enablers (14) and economic support (11) are crucial for promoting alternative fuels, but regulatory barriers (18) and economic support barriers (13) highlight the challenges in aligning policies and securing financial incentives.

While strong drivers for the adoption of alternative fuels exist, significant challenges remain. Addressing technical, infrastructure and environmental barriers is essential for leveraging the identified enablers and promoting sustainable fuel adoption in the maritime industry.

4.1.4 A decision-making framework for the adoption of alternative fuels

The adoption of alternative fuels in the maritime industry is a multifaceted process shaped by a complex interplay among various parts. This framework, Figure 22, offers a comprehensive view of the interconnected elements that influence the transition towards low-carbon fuels. It includes eight key groups: maritime industry stakeholders, institutional pressures, models and tools for decision-making, alternative fuels, facilitators and enablers, challenges and barriers, criteria adopted, and outcomes and results. Each component of the framework plays a crucial role in the overall decision-making process. By examining these components and their interactions, the framework highlights the dynamic relationships that drive decision-making and implementation strategies within the maritime sector. Understanding the whole, the parts, and the interplay among them is essential for comprehending the pathways to sustainable maritime operations and identifying leverage points for effective intervention and policy-making.

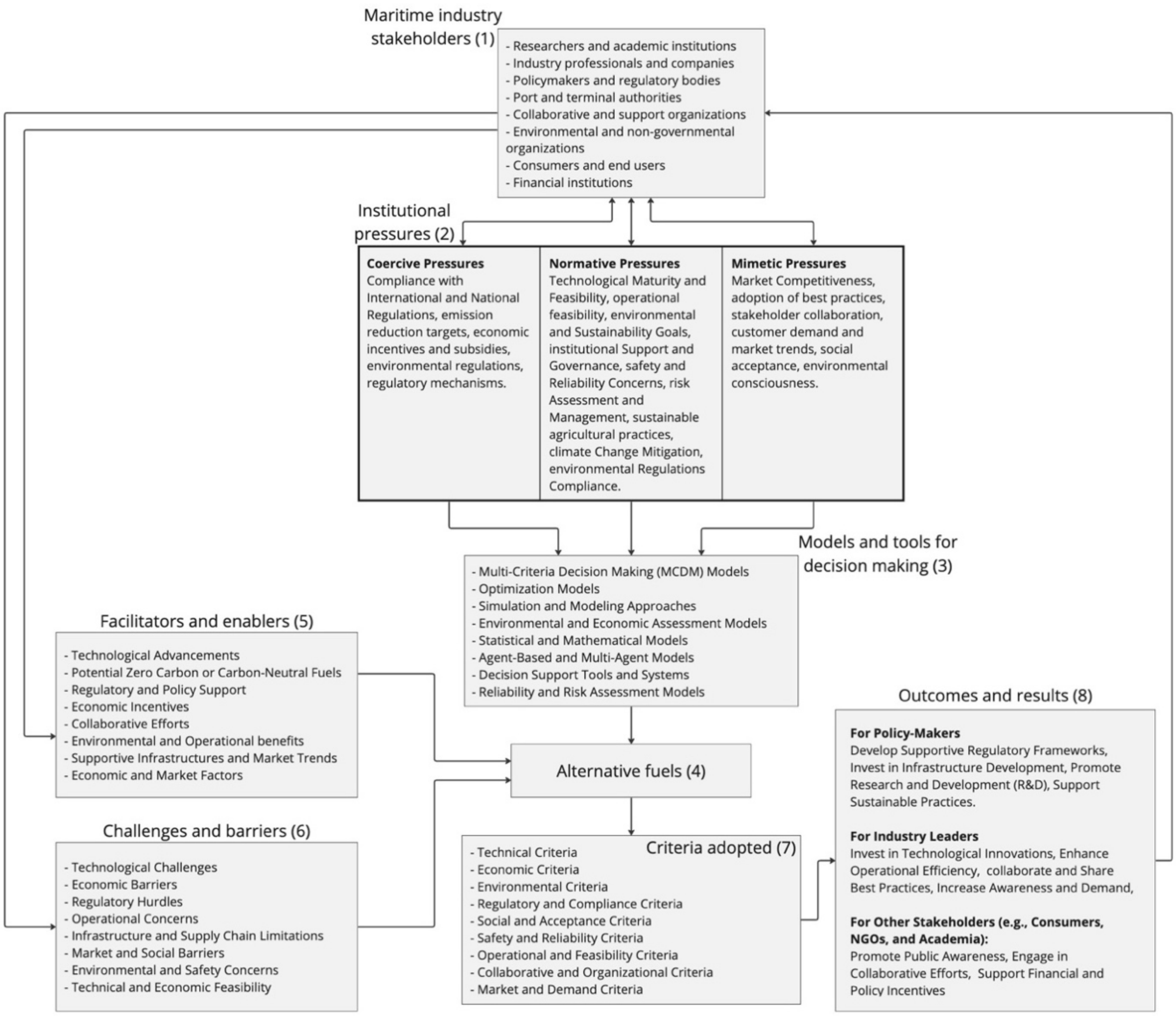

Figure 22: A framework illustrating the interconnected elements influencing the adoption of alternative fuels in the maritime industry.

4.1.4.1 Maritime Industry Stakeholders (1)

Stakeholders such as shipowners, operators, fuel suppliers, and regulatory bodies play a crucial role in shaping the industry's direction. Their decisions and actions create institutional pressures (2), which drive the adoption of alternative fuels. For instance, the IMO has set targets for the reduction of GHG emissions, and the maritime industry has developed an engine for a specific type of fuel.

The outcomes and results (8) of adopting alternative fuels provide feedback to stakeholders, influencing future decisions and strategies; for instance, when the society has perceived the move for emissions reduction as conservative or slow, IMO has revised its emissions reduction targets, adopting more restrictive measures. This feedback loop ensures continuous improvement and adaptation within the industry, for instance, the move of the OEM to provide products (engines, parts, systems) that are in line with the environmental and operational restrictive measures and according to the market demand.

4.1.4.2 Institutional Pressures (2)

Institutional pressures directly affect stakeholders by imposing regulations, norms, and market expectations. These pressures compel stakeholders to consider alternative fuels and sustainable practices.

The need to comply with these pressures drives the development and application of specific models and tools for decision-making (3). For instance, regulatory compliance requirements may necessitate the use of lifecycle assessment models to evaluate environmental impacts.

4.1.4.3 Models and tools for decision-making (3)

Different decision-making models are suited to different types of problems and alternative fuels (4). For example, optimization models may be used to minimize costs for LNG adoption, while scenario analysis could assess the long-term impacts of hydrogen fuel.

The choice of model influences the criteria adopted (7). For instance, lifecycle assessment may prioritize environmental sustainability, while economic assessment models focus on cost-effectiveness.

4.1.4.4 Alternative fuels (4)

Fuel-specific characteristics: Each alternative fuel has unique characteristics that present specific enablers (5) and challenges (6). For example, LNG might be supported by existing infrastructure (enabler) but face high initial investment costs (challenge).

Criteria suitability: Depending on the fuel type, different criteria become more relevant. Hydrogen fuel adoption might prioritize emissions reduction, whereas biodiesel may focus on operational feasibility and cost.

4.1.4.5 Facilitators and enablers (5)

Support mechanisms: Facilitators such as technological advancements, economic incentives, and policy support make the adoption of alternative fuels more feasible. These enablers are often influenced by stakeholder actions and institutional pressures.

Interdependence with challenges: Enablers and challenges are interdependent. For example, advancements in technology (enabler) can mitigate operational concerns (challenge), while economic incentives (enabler) can counterbalance high initial costs (challenge); for instance, LNG is one fuel that has experienced economic incentives to accelerate its adoption due to initial high capital costs necessary.

4.1.4.6 Challenges and barriers (6)

Obstacles to adoption: Challenges such as technological limitations, economic barriers, and regulatory hurdles impede the adoption of alternative fuels. These barriers are identified and addressed through decision-making models and stakeholder collaboration.

Influence on outcomes: The presence of challenges directly affects the outcomes and results (8). Effective mitigation strategies enhance the likelihood of successful adoption and positive outcomes.

4.1.4.7 Criteria adopted (7)

Decision-making basis: Criteria such as cost, environmental impact, and regulatory compliance guide the decision-making process. The selection of criteria is influenced by the type of alternative fuel and the decision-making model employed, as shown in Table 8.

Outcome measurement: The criteria also serve as benchmarks to evaluate the success of the adoption process. They help in assessing whether the chosen alternative fuel meets the desired goals and regulatory standards.

4.1.4.8 Outcomes and Results (8)

Feedback to stakeholders: The outcomes of adopting alternative fuels provide valuable feedback to stakeholders, informing future decisions and adjustments in strategies. Positive outcomes reinforce the adoption process, while negative outcomes highlight areas for improvement.

Influence on Institutional Pressures: Successful adoption and positive results can lead to changes in institutional pressures, such as updated regulations and increased market acceptance, thereby influencing the entire framework.

4.1.4.9 Testing the framework: importance and methodology

The proposed framework provides a theoretical basis for understanding the decision-making process involved in adopting alternative fuels in the maritime industry. However, to ensure its practical relevance and effectiveness, it is crucial to test this framework with industry stakeholders. Empirical validation will provide valuable insights and facilitate the refinement of the framework, enhancing its applicability and robustness.

Engaging with industry stakeholders allows for the collection of primary data on the decision-making processes and the maritime industry value chain. This empirical approach will help identify potential gaps, validate assumptions, and improve the framework's components. Additionally, feedback from industry players can reveal practical challenges and enablers that may not be fully captured in theoretical models.

To achieve this, a structured interview script has been designed. This script is tailored to elicit detailed information from industry stakeholders about their experiences, decision-making processes, and perspectives on the adoption of alternative fuels. The insights gained from these interviews will be instrumental in refining the framework, ensuring it accurately reflects the complexities and realities of the maritime sector.

The interview script, which is designed to test the framework among industry players, is included in the Appendix C. It encompasses questions that explore the decision-making process, the roles and influences of various stakeholders, institutional pressures, and the criteria used in adopting alternative fuels. This structured approach ensures comprehensive data collection, facilitating the continuous improvement of the framework.

4.2 Survey on sustainable purchasing in the Brazilian maritime industry

The survey results provide a comprehensive overview of the adoption and implementation of sustainable purchasing practices (SPP) within the Brazilian maritime industry. Through the examination of responses from 90 organizations, this section aims to highlight key findings on the importance, prevalence, and influences of SPP. The survey captured the perspectives of professionals involved directly or indirectly in procurement, offering insights into current sustainability trends and priorities. By analysing the significance of sustainability in procurement processes and the influence of various drivers, the results show the industry's commitment to sustainability and the attempt to transition such practices from niche to a new operational regime.

The results reveal a social-technical landscape where larger private organizations, particularly in logistics and manufacturing, are at the forefront of sustainability efforts, supported by contributions from consultancy, research, and educational institutions. This diverse representation confirms the multifaceted nature of sustainability in the maritime sector and the collaborative efforts required to advance sustainable practices.

Table 10 shows the characteristics of the organizational respondents, comprising a total of 90 organizations engaged in sustainability practices, reveals a diverse representation predominantly characterized by a significant presence of large companies (n=48) and entities within the transportation and logistics sector (n=48), underscoring this sector's pivotal role in sustainability efforts. The sample is primarily composed of private sector entities (n=76), indicating a robust engagement from private enterprises in sustainability initiatives. Despite the lesser representation of small businesses (n=8) and government and regulatory bodies (n=3), the inclusion of various company sizes and sectors, including industry and manufacturing (n=22), consultancy and services (n=9), and research, development, and education (n=8), underscores the comprehensive approach of the study towards understanding sustainability practices across different organizational contexts. This distribution suggests a landscape where larger private organizations, particularly in logistics and manufacturing, are leading participants in sustainability, with a noteworthy contribution from non-profit and educational institutions (n=5), emphasizing the role of innovation, knowledge dissemination, and advisory services in promoting sustainable practices.

Table 10: Respondent profile by sector, size and ownership.

Maritime sectors	**Total**	**Percentage (%)**
Transportation and logistics	48	53.3
Industry and manufacturing	22	24.5
Consultancy and services	9	10.0
R&D and education	8	8.9
Government and regulatory bodies	3	3.3
Total	90	100
Size (number of employees)		
> 500	48	53.3
50 – 500	19	21.1
10 – 49	15	16.7
< 9	8	8.9
Total	90	100
Ownership		

Maritime sectors	Total	Percentage (%)
Private companies	76	84.4
State-owned	9	10.0
Non-profit and education	5	5.6
Total	90	100

4.2.1 Sustainability perception among respondents

At the beginning of the survey, respondents were asked to evaluate their perception of the importance of sustainability in their companies' purchasing practices as of today and what they understand the importance of sustainability will be in the future. In order to compare the results, the correlation among the set of variables was established, measuring the correlation of the importance of sustainability today against all the SPPs and the importance of sustainability in the future against the same SSPs. The results and the correlation factors are shown in Table 11 below.

Table 11: Correlation matrix of sustainability perception and SPPs.

	Sustainability today	Sustainability future
DGSP	0,62	0,38
TPES	0,52	0,40
ISPP	0,64	0,36
SCC	0,44	0,40
WSP	0,54	0,44
MDPP	0,68	0,44
SSI	0,57	0,41
SSD	0,36	0,35
ISOCERT	0,31	0,26
PHRS	0,61	0,42

In general, a stronger correlation with current sustainability perception was found. Internal Sustainable Purchase Processes (SPPs) such as Developed goals for sustainable purchasing (DGSP), Training for purchasing employees on sustainability impacts (TPES), and Integration of sustainability into the procurement process (ISPP) show stronger correlations with current sustainability perception compared to future sustainability perception. Based on this finding, companies that realise the current importance of sustainability and how it can affect their businesses - the current social-technical regime is transitioning to sustainable operations – have started to adapt and "revolutionise" the industry by adopting such sustainable practices.

While Internal SPPs like Measures to develop sustainability-focused purchasing policies (MDPP) and Supplier sustainability information (SSI) show moderate correlations with future sustainability perception, they still indicate a positive relationship between these practices and the importance of sustainability in the future. It implies that companies recognize the significance of these practices in shaping their future sustainability strategies.

External Sustainable Purchase Practices (SPPs) such as Supplier sustainability development (SSD) and ISO14001 certification (ISO-Cert) exhibit weaker correlations with both current and future sustainability perceptions. This suggests that these external practices may have a less pronounced impact on how sustainability is perceived in both the present and the future within companies.

Some SPPs, like Written policy on sustainable procurement (WSP) and Preference for highly-rated sustainability suppliers (PHRS), show relatively consistent correlations with both current and future sustainability perceptions. This indicates that these practices are perceived as important for sustainability initiatives both now and in the future.

Overall, the differences in correlations between current and future sustainability perceptions suggest that while certain internal practices are currently more influential in shaping sustainability strategies within companies, there is a recognition of the importance of specific practices for future sustainability initiatives.

When assessing the results of the drivers for the adoption of sustainability, comparing the overall results from the sustainability today and sustainability future variables, the strength of correlations for most of the drivers are slightly higher for sustainability future compared to sustainability today, as shown in Table 12. This suggests that respondents may perceive sustainability to be slightly more important in the future than it is today.

Table 12: Correlation of sustainability perception and enablers.

	Sustainability today	**Sustainability future**
REP	0,47	0,56
MET	0,41	0,41
BENC	0,40	0,35

	Sustainability today	Sustainability future
AGLR	0,36	0,41
CGLR	0,22	0,22
CEOVP	0,45	0,37
Economic Costs	0,20	0,16
CSP	0,17	0,11
TPP	0,20	0,17

The drivers that show a more noticeable difference in correlation strength between sustainability today and sustainability future are Company President's Vision (CEOVP) and Economic Costs. CEOVP has a higher correlation with sustainability today, indicating that the company president's vision may currently have a stronger influence on how sustainability is perceived. On the other hand, Economic Costs have a slightly higher correlation with sustainability future, suggesting that cost considerations may become more important in the future perception of sustainability.

The drivers that show consistent and similar correlations with both sustainability today and sustainability in the future include Company Reputation (REP), Moral/Ethical Motivation (MET), and Leadership in Best Practices (BENC). This consistency indicates that these factors are perceived as equally important in both the present and future contexts of sustainability.

Anticipated Government Legislation/Regulation (AGLR) and Current Government Legislation/Regulation (CGLR) show slightly higher correlations with sustainability in the future compared to sustainability today. This suggests that respondents may anticipate a stronger impact of government regulations on sustainability practices in the future.

Customer Pressure (CsP) and Pressure from Third Parties (TPP) have relatively low correlations with both sustainability today and sustainability future, indicating that external pressures from customers and third parties may not be perceived as significant drivers of sustainability importance by the respondents or that the respondents' companies have not yet suffered pressure from costumers.

The comparison of the overall results between sustainability today and sustainability in the future reveals a nuanced perspective on how the respondents perceive the importance of sustainability. While there is a general trend of slightly higher correlations with sustainability in the future, indicating a future-oriented view of sustainability importance, certain drivers show varying degrees of influence on the present and future perceptions of sustainability.

4.2.2 Prioritization of products and services

In examining the sustainable procurement practices within the maritime industry, the analysis revealed the prioritization of products and services, as shown in Figure 23. Fuels emerged as the paramount concern, with a mean score of 4.61, reflecting the industry’s focus on energy efficiency and emission reductions, thus confirming the findings of the previous qualitative studies. Maintenance services and safety equipment also garnered significant attention, scoring 4.36 and 4.33, respectively, underscoring the value placed on sustainable operations, safety measures and compliance. While dredging services and information technology were considered moderately important, office materials and communication equipment, both scoring a mean of 3.8, were deemed less critical in sustainability considerations.

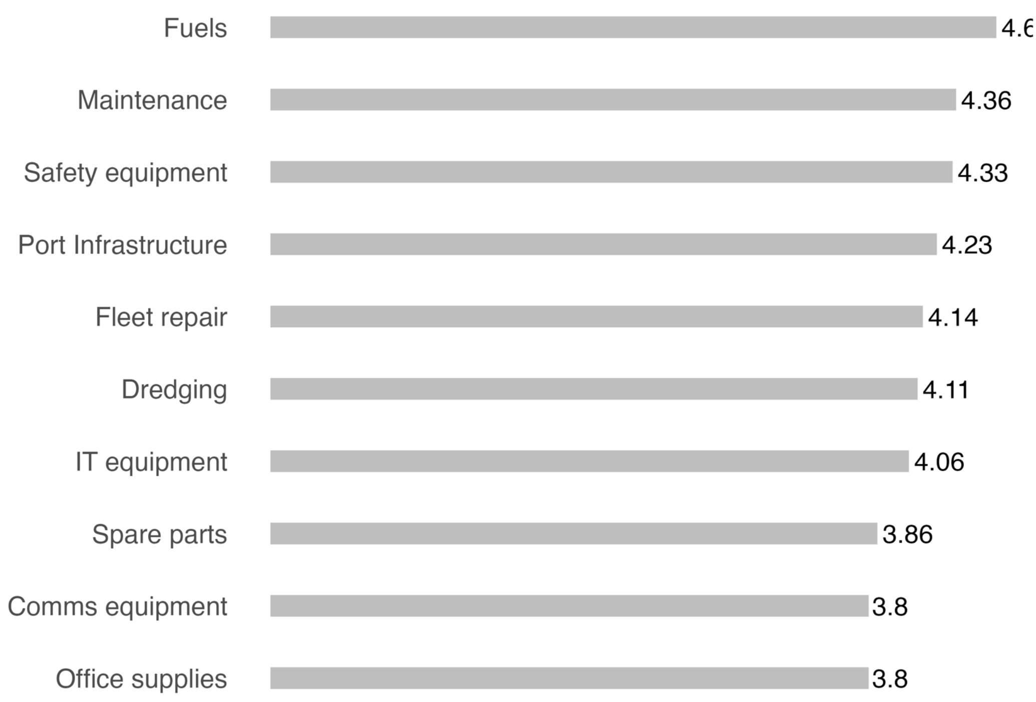

Figure 23: Mean scores of products and services.

The survey results on the correlation matrix among services and products for sustainable purchasing practices reveal several noteworthy relationships within a 95% confidence interval. These positive correlations indicate areas where respondents perceive interdependencies or similarities in importance regarding sustainability. Figure 24 shows the correlations, and the relationships with statistical significance are shown with a blue circle, according to the colour scale.

One of the most prominent findings is the strong correlation between spare parts and fleet repair, with a value of 0.7878 and a p-value of 0.9799. Respondents who value sustainable spare parts are also likely to prioritize fleet repair, reflecting an integrated approach to maintenance and sustainability in logistics and transport operations.

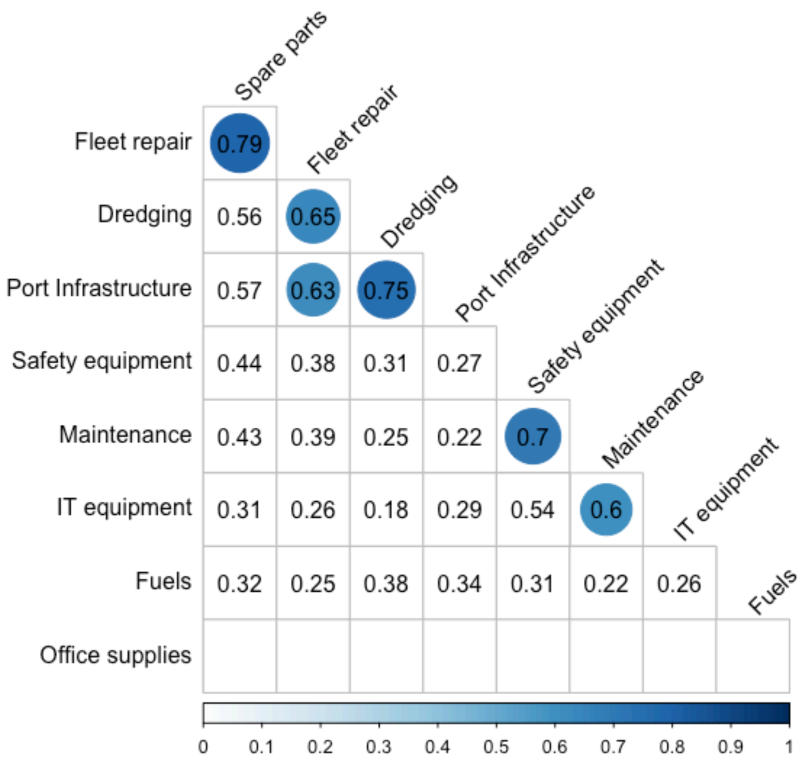

Figure 24: Correlation among the services and products for sustainability.

In addition, the correlation between fleet repair and dredging stands out at 0.6495, with a p-value of 0.9284, suggesting that maintaining the fleet and ensuring navigable waterways are interdependent aspects of sustainable practices in maritime operations.

The correlation between Fleet Repair and Port Infrastructure is significant, with a value of 0.6270 and a p-value of 0.9274. This indicates a strong relationship, suggesting that respondents who prioritize fleet repair also place importance on port infrastructure. This correlation reflects the interconnected nature of maintaining both the fleet and the supporting infrastructure to ensure efficient and sustainable maritime operations. The correlation between dredging and port infrastructure is also notable at 0.7489, with a p-value of 0.9741, reflecting the essential role of both in sustaining maritime transport efficiency.

The correlation between Safety Equipment and Maintenance is even more pronounced, with a value of 0.6999 and a p-value of 0.9645. This strong correlation emphasizes the critical link between safety equipment and maintenance practices. Respondents likely recognize that maintaining high safety standards is integral to effective maintenance operations, highlighting the interdependence of these two aspects in achieving overall operational efficiency and safety.

The relationship between Maintenance and IT Equipment is also noteworthy, with a correlation of 0.6007 and a p-value of 0.9244. This strong correlation suggests that respondents see a significant connection between maintenance activities and the use of IT equipment. The integration of IT equipment in maintenance practices is likely perceived as essential for enhancing efficiency, monitoring, and overall sustainability of operations.

4.2.3 Sustainable purchasing practices

The results of the survey on sustainable purchasing practices (SPP) among respondents are presented in this section.

Figure 25 provides a visual representation of the frequency of responses from a survey on sustainable purchasing practices among respondents. The chart categorizes responses into three groups: those that have fully implemented the practice “Yes”, those that are currently developing it “Under development”, and those that have not adopted the practice “No”.

The data presented offers a comprehensive overview of the sustainable purchasing practices adopted by companies, reflecting their efforts towards integrating sustainability into their procurement processes.

The majority (31) of companies have developed suppliers focused on sustainability, indicating a proactive approach towards ensuring their supply chains are aligned with sustainable practices. However, a significant portion (16) has not initiated such efforts, suggesting room for improvement. The 13 companies currently developing these suppliers reflect a growing trend towards sustainable procurement.

A substantial number of companies (28) prefer suppliers with high sustainability ratings, emphasizing the importance of supplier evaluation in sustainability efforts. The presence of 15 companies still developing this preference suggests ongoing progress, while 17 companies not prioritizing highly-rated suppliers highlight a gap in sustainable supplier selection.

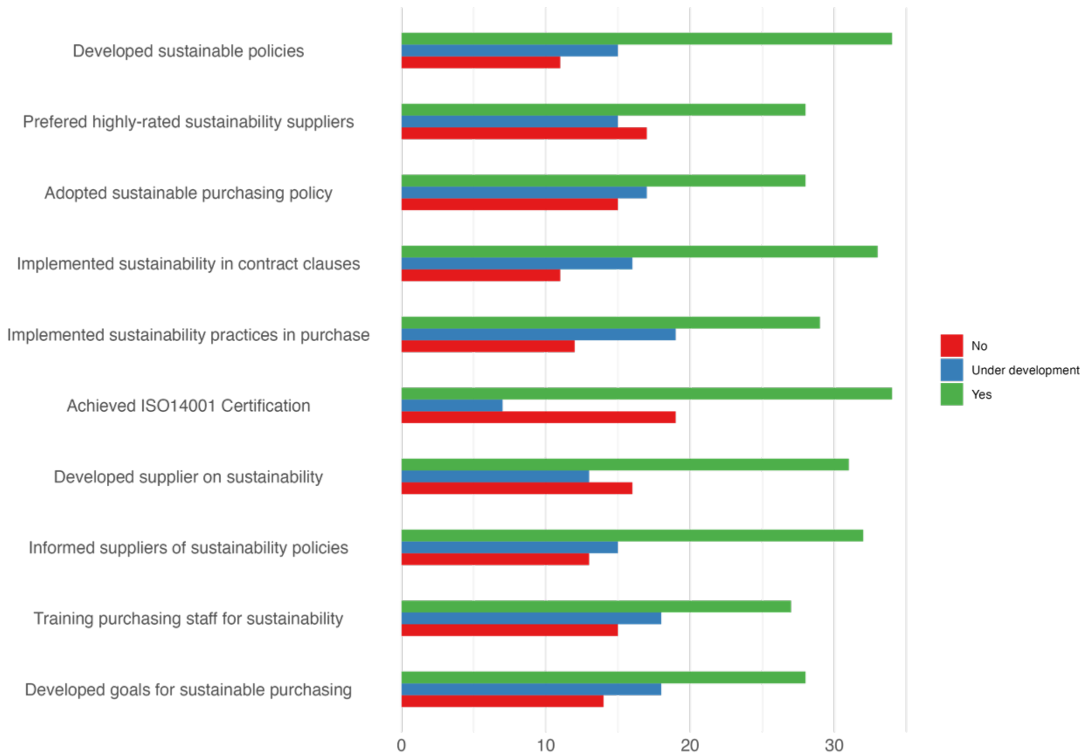

Figure 25: Sustainable purchasing practices among respondents.

Achieving ISO14001 certification is a significant indicator of a company's dedication to environmental management. With 34 companies certified, this practice is well-regarded. However, the 19 companies without certification point to a notable deficiency in formal environmental management systems, which could be a critical area for development.

Sustainable policy development is widespread, with 34 companies having established such policies. This demonstrates a strong foundation for sustainability within these organizations. The 15 companies in the development phase suggest ongoing efforts, while the 11 without policies underscore the need for more comprehensive policy adoption.

Setting goals for sustainable purchasing is essential for guiding company efforts. The 28 companies with established goals reflect a strategic approach, whereas the 18 in development signify ongoing planning processes. The 14 without goals highlight the necessity for clearer sustainability objectives within some organizations.

The adoption of sustainable purchasing policies is evident in 28 companies, showcasing their commitment to integrating sustainability into procurement. The 17 developing policies and the 15 without such policies indicate varying stages of policy implementation and adoption across the board.

The implementation of sustainability in contract clauses by 33 companies demonstrates a formalized approach to ensuring sustainable practices are legally enforced. The 16 companies developing this practice indicate progressive efforts, while the 11 without such clauses suggest a potential area for enhancement.

A total of 29 companies implementing sustainability practices in their purchases reflects a substantial commitment to sustainable procurement. The 19 developing these practices and the 12 without them highlight the varying degrees of integration and the potential for broader adoption.

Training purchasing staff for sustainability is critical for effective implementation. The 27 companies conducting training exhibit a proactive approach to building internal capabilities. The 18 in development and the 15 not conducting training point to ongoing efforts and gaps that need addressing.

While the data reveals a commendable level of engagement in sustainable purchasing practices, it also highlights significant areas for improvement. The varying stages of development across companies suggest that while sustainability is gaining traction, consistent and comprehensive adoption remains a challenge. Key areas such as achieving ISO14001 certification and training purchasing staff require more focused efforts to ensure broader, more impactful integration of sustainability into procurement practices.

Table 13 shows the results of descriptive statistics on pressure, SPP and economic performance. The average scores for institutional pressures indicate a relatively high level (4=important; 5=very important) of recognition of these pressures among maritime professionals, with coercive pressures (M=4.14, SD=0.80) and normative pressures (M=4.15, SD=0.59) being almost equally acknowledged. Mimetic pressures were reported to have the highest influence on the sample (M=4.26, SD=0.87), suggesting that there is a considerable degree of observation and emulation of practices among industry peers.

Table 13: Descriptive statistics on pressure, SPP and performance.

Factors		**Mean**	**Std. Dev.**
Institutional pressure			
	Coercive	4.14	0.80
	Normative	4.15	0.59
	Mimetic	4.26	0.87
Internal drivers			
	Company President's Vision (CEOVP)	4.26	1.02
	Moral/Ethical Motivation (MET)	4.38	0.80
External drivers			
	Anticipated Government Legislation/Regulation (AGLR)	4.14	0.86
	Current Government Legislation/Regulation (CGLR)	4.13	0.93
	Company Reputation (REP)	4.57	0.70
	Customer Pressure (CsP)	3.92	0.88
	Pressure from Third Parties (TPP)	3.63	0.99
	Leadership in Best Practices (BENC)	4.26	0.87
SPP			
	Sustainable purchasing (DGSP)	3.16	2.02
	Training for purchasing employees (TPES)	2.77	2.12
	Sustainability into the procurement process (ISPP)	3.09	1.95
	Sustainability clauses in contracts (SCC)	3.33	1.96
	Written policy on sustainable procurement (WSP)	3.16	2.03
	Sustainability-focused purchasing policies (MDPP)	3.55	1.90
	Supplier sustainability information (SSI)	3.28	2.03
	Supplier sustainability development (SSD)	3.15	2.13
	ISO14001 certification (ISO-Cert)	3.08	2.29
	Preferer highly-rated sustainability suppliers (PHRS)	2.90	2.17
Performance			
	Cost savings	4.22	0.88

Note 1: Pressure/ drivers/ performance; 1=very weak, 2=weak, 3=neutral, 4=strong, 5=very strong
Note 2: Practices; 0=not implemented, 2.5=under development, 5=implemented

The vision of the company president (CEOVP) and moral/ethical motivation (MET) were reported as significant internal drivers, with means above 4, highlighting the importance of leadership and ethical considerations in driving sustainable internal procurement within organizations. External drivers encompass anticipated and current government legislation, company reputation, customer pressure, and pressure from third parties. Company reputation (REP) emerged as a prominent driver, with the highest mean (M = 4.57) and the lowest standard deviation (SD = 0.70), signalling a strong and consistent influence across the sample. In contrast, pressure from third parties (PTP) exhibited the lowest mean (M = 3.63) and the highest standard deviation (SD = 0.99), suggesting that its influence on sustainable procurement practices is less pervasive and more variable.

SPP varied widely in their reported implementation, as evidenced by moderate means and high standard deviations. The most consistently reported practice was sustainability-focused purchasing policies (MDPP), with a mean of 3.55. In contrast, the preference for highly-rated sustainability suppliers (PHRS) had the lowest mean (M = 2.90), coupled with a high standard deviation (SD = 2.17), indicating considerable variability in its adoption.

Cost savings, as a performance outcome, reported a high mean (M = 4.22), suggesting that SPP are generally expected to contribute to economic efficiency. However, the variation in responses (SD = 0.88) points to differing levels of cost savings achieved by organizations, which may be influenced by the extent and effectiveness of SPP implementation.

5 Discussion

This study sought to understand the decision-making processes involved in adopting alternative fuels in the maritime industry, guided by institutional theory, MLP and pragmatic ontology. The primary research questions focused on identifying the key factors influencing this transition and the role of institutional pressures and practical considerations in shaping stakeholder decisions. The main findings indicate a significant impact of regulatory, normative, and mimetic pressures, as well as the crucial importance of feasibility, cost-effectiveness, and practical implementation in the adoption of alternative fuels. The MLP framework provided useful lens for analysing the results, as it considered the interactions between three levels: the niche (where radical innovations emerge), the regime (the dominant practices and technologies), and the landscape (the broader social, economic, and political context).

This section integrates the empirical findings of the scoping review and the survey with the theoretical frameworks of MLP and Institutional Theory to discuss the adoption of alternative fuels in the maritime industry. Figure 26 illustrates the complex interactions between the socio-technical landscape, regime, and niches within this industry, mapping out how these interactions are influenced by broader institutional pressures and emerging innovations.

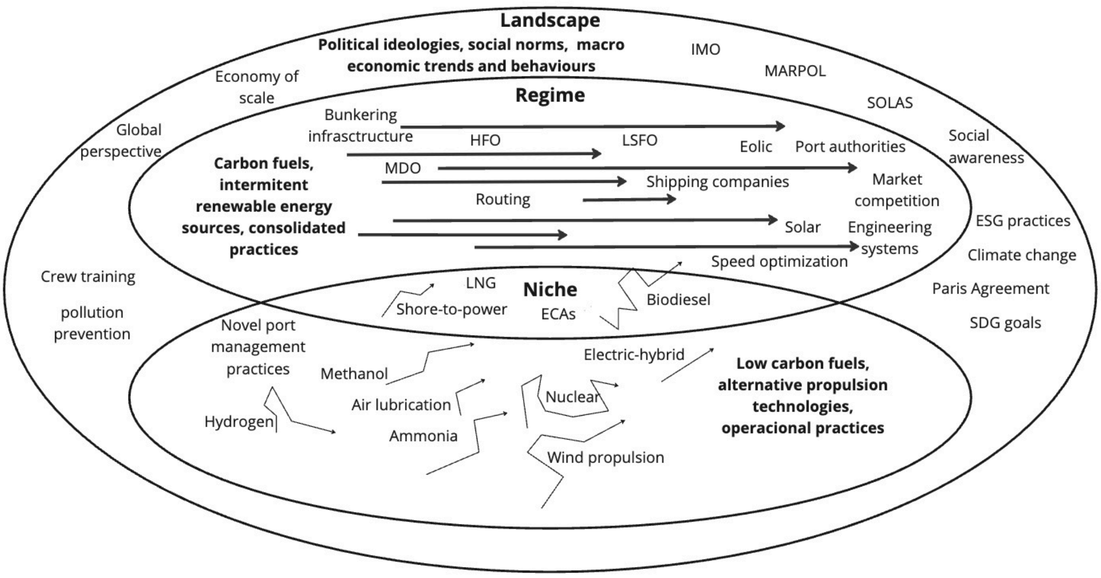

Figure 26: MLP framework for maritime sustainable transition.

The MLP framework provides a robust structure for understanding the dynamics of technological transitions within socio-technical systems. In the maritime industry, the socio-technical landscape encompasses not only global regulatory measures and environmental mandates but also macro-economic shifts and advances in related technologies. These elements exert coercive pressures as described by DiMaggio & Powell (1983), pushing the industry towards compliance with increasingly stringent environmental standards.

The regime, consisting of established fuel technologies, operational practices, and infrastructural norms, interacts dynamically with these pressures. The slow pace of change within regimes, as highlighted by both MLP and Institutional Theory, is due to the path dependency and the entrenched interests of established stakeholders. These stakeholders include shipping companies, port authorities, and regulatory bodies that rely on existing infrastructures and technologies, which align with the normative pressures that encourage adherence to traditional norms and practices.

Within the niches, innovative practices and technologies such as LNG, hydrogen, ammonia, and biofuels are developed. These represent radical innovations that Institutional Theory identifies as emerging from “protected spaces” — experimental and pilot projects supported by niche actors, including research institutions and startups. These spaces allow for the experimentation and development of alternatives that can challenge the status quo, illustrating the concept of mimetic pressures where organizations mimic successful innovations to gain competitive or regulatory advantages.

Integrating Institutional Theory with MLP enriches the understanding by highlighting how institutional pressures (coercive, normative, and mimetic) not only shape but are also shaped by the technological trajectories within the maritime industry. Figure 26 underscores this interplay, showing the potential for niche innovations to disrupt the existing regime through the influence of institutional pressures, thereby leading to a shift in the socio-technical landscape itself.

The discussion around alternative fuels in the maritime industry is not just about technological substitution but also about institutional alignment and conflict. For example, while the introduction of sulphur cap regulations by the IMO can be seen as a coercive change prompting shifts in fuel use, the industry's response — whether through adoption of scrubbers or switching to low-sulphur fuels —

depends significantly on the existing regime's structure and the viability of niche innovations.

Institutional theory provided a robust framework for understanding how various pressures influence the adoption of alternative fuels in the maritime industry. Coercive pressures, such as stringent regulations from international bodies like the IMO, compel to maritime industry to adopt cleaner technologies to comply with environmental standards and climate change goals. These findings align with DiMaggio & Powell (1983) concept of coercive isomorphism, demonstrating how regulatory pressures from IMO compel the maritime industry to adopt cleaner technologies to comply with environmental standards. The survey results highlighted that regulatory compliance is an important driver for adopting alternative fuels, reflecting the significant influence of these coercive pressures. Zucker (1987) supports this, emphasizing that regulatory compliance enhances organizational legitimacy and survival prospects by aligning with broader societal goals. From an MLP perspective, these coercive pressures can be seen as landscape developments that create windows of opportunity for niche innovations to challenge the existing social-technical regime.

Normative pressures also play a crucial role. Industry standards, best practices promoted by academic institutions, and guidelines from classification societies create a normative framework that encourages the adoption of sustainable practices. The high publication output in journals focused on sustainability, such as the Journal of Cleaner Production and Energies, underscores the importance of normative pressures in disseminating knowledge and best practices. Zucker (1987) highlights that normative pressures arise from professional bodies and academic institutions, establishing standards that organizations must meet to gain legitimacy and support from their stakeholders. These normative pressures can be understood within the MLP as part of the socio-technical regime that guides industry practices and expectations (Geels, 2020; A. Smith et al., 2010).

Mimetic pressures are evident as maritime companies seek to emulate the successful strategies of their peers. The study found that company reputation and customer pressure are significant external drivers, indicating that organizations are motivated to adopt alternative fuels to enhance their competitive edge and meet stakeholder expectations. The MLP framework highlights how niche innovations can gain momentum as companies imitate each other's successful strategies, leading to wider regime shifts (Mignon & Kanda, 2018; Raven, 2006). Zucker (1987) discusses how organizations imitate successful strategies of their peers to reduce uncertainty and enhance their legitimacy, further supporting the findings of this study. Sarkis et al. (2011) also highlight that competitive pressures (mimetic pressures) lead to the adoption of green practices, which can improve economic performance without compromising environmental goals. This is also found in the survey conducted in the Brazilian setting, where the local industry adopts sustainable purchasing practices to improve economic performance.

Pragmatic ontology emphasizes the practical considerations and real-world applicability of adopting alternative fuels. The findings reveal that feasibility and cost-effectiveness are paramount in decision-making processes. High initial costs and infrastructure limitations are major barriers, while economic incentives and technological advancements are critical enablers. The MLP framework can be applied here to understand how practical considerations at the niche level interact with regime and landscape factors to influence adoption decisions, such as lock-in mechanisms (Unruh, 2000).

The practical implementation of alternative fuels requires a careful assessment of their technical and economic viability. The use of decision-making models, such as the Analytic Hierarchy Process (AHP) and Lifecycle Assessment (LCA), helps stakeholders evaluate these factors comprehensively. The research underscores the importance of practical solutions that address these barriers, highlighting the need for technological innovations and supportive regulatory frameworks.

This study contributes to institutional theory by providing new insights into how institutional pressures operate specifically within the maritime industry. The unique regulatory environment and the global nature of maritime operations necessitate a rethinking of how coercive, normative, and mimetic pressures interact. Zhu et al. (2007) emphasize the need to consider multiple institutional pressures simultaneously, as they interact to shape organizational responses and performance outcomes. The findings suggest that the maritime industry is heavily influenced by international regulations, which may require extending institutional theory to account for the significant role of global governance in shaping industry practices. The MLP framework supports this extension by illustrating how landscape-level pressures (e.g., international regulations) shape regime dynamics and create opportunities for niche innovations.

The findings from Reid & Toffel (2009) provide valuable support for the argument that global regulatory environments necessitate a rethinking of institutional theory, particularly within the maritime industry. Their study demonstrates that both public and private political pressures can significantly influence corporate disclosure practices regarding climate change. Specifically, the threat of state regulations and the actions of activist groups have been shown to spur firms to adopt new environmental practices. This dual influence highlights the critical role of global governance and regulatory threats in driving organizational change and enhancing transparency (Reid & Toffel, 2009). The evidence suggests that firms respond not only to direct regulatory pressures but also to the broader industry-level implications of shareholder resolutions and potential regulations. These dynamics indicate that the maritime industry's global operations and regulatory context amplify the effects of coercive, normative, and mimetic pressures, thus requiring an extension of institutional theory to fully capture the impact of international governance frameworks on industry practices (Reid & Toffel, 2009).

MacLeod (2001) discusses the concept of "relativization of scale" that highlights how the restructuring of state functions in response to globalization does not diminish the role of the state but reconfigures it across different scales, from the global to the local. In the maritime sector, this means that international regulations must be interpreted and enforced within various national and regional contexts. This interplay requires maritime companies to navigate not only the broad mandates of global regulations but also the specific requirements and constraints of local authorities, such as, port authorities, country level policies, European Union. For instance, while the IMO may mandate cleaner technologies to reduce emissions, the practical implementation of these technologies must consider local infrastructural capacities and economic conditions. This dynamic underscore the need for a nuanced approach to institutional theory that accounts for both the overarching influence of international governance and the localized realities of implementation. Critically, it reveals that the effectiveness of global regulations hinges on the ability to adapt and enforce them at the local level, necessitating a comprehensive understanding of both global and local dynamics (MacLeod, 2001).

The findings support and refine the pragmatic approach to understanding decision-making by emphasizing the importance of practical considerations. Feasibility, cost-effectiveness, and real-world applicability emerged as the most significant factors influencing the adoption of alternative fuels. This study highlights the need for a pragmatic framework that integrates these practical considerations into the decision-making process, providing a more comprehensive understanding of how stakeholders tackle complex technological transitions. The MLP framework complements this pragmatic approach by illustrating how niche innovations must align with regime structures and landscape developments to achieve practical implementation and generate new social-technical regimes.

The results of the survey on sustainable purchasing practices (SPP) within the Brazilian maritime industry reveal significant insights into how organizations are integrating sustainability into their procurement processes and the various drivers influencing these practices. By interpreting these findings through the lenses of institutional theory and the Multi-Level Perspective (MLP) framework, the mechanisms and dynamics underpinning the industry's sustainability transition are better understood.

The Brazilian maritime industry exhibits clear mimetic, coercive, and normative pressures influencing its sustainability practices. Mimetic pressures are evident as companies look towards international benchmarks and adopt proven practices such as cleaner fuel technologies, ballast water management systems, and greenhouse gas emission reduction strategies. These practices not only enhance environmental outcomes but also align Brazilian companies with global sustainability standards, fostering a culture of innovation and continuous improvement.

The survey results underscore the importance of mimetic pressures, with respondents indicating a high influence of industry peers and best practices on their sustainability strategies (Mimetic Mean = 4.26, SD = 0.87). This aligns with the notion that organizations often emulate successful counterparts to enhance their legitimacy and competitive advantage. The strong correlation between current sustainability perception and internal SPPs, such as developed goals for sustainable purchasing (DGSP) and integration of sustainability into the procurement process (ISPP), further supports this view. These internal practices show stronger correlations with current sustainability perceptions compared to future perceptions, suggesting that companies are actively adapting to the current social-technical regime and revolutionizing the industry by adopting sustainable practices.

Coercive pressures, derived from regulatory requirements and government legislation, also play a significant role. The survey highlights that anticipated government legislation (AGLR) and current government legislation (CGLR) have high mean scores, indicating their importance as drivers of sustainability (AGLR Mean = 4.14, SD = 0.86; CGLR Mean = 4.13, SD = 0.93). This suggests that regulatory frameworks are critical in shaping the sustainability landscape, compelling companies to comply with environmental standards to avoid penalties and enhance their market position.

Normative pressures, stemming from professional norms and ethical considerations, are reflected in the high mean scores for moral/ethical motivation (MET) and company reputation (REP). These drivers emphasize the importance of ethical standards and reputational concerns in promoting sustainable practices (MET Mean = 4.38, SD = 0.80; REP Mean = 4.57, SD = 0.70). The strong influence of normative pressures indicates that sustainability is increasingly viewed as a moral and social obligation within the maritime industry.

The MLP framework provides a complementary perspective by examining the interaction between different levels of socio-technical systems: the niche, regime, and landscape. The survey results reveal a socio-technical landscape where larger private organizations, particularly in logistics and manufacturing, are at the forefront of sustainability efforts. These organizations, supported by contributions from consultancy, research, and educational institutions, are driving the transition from niche innovations to a new operational regime.

Niche innovations, such as advanced fuel technologies and sustainable procurement practices, are being developed and adopted by pioneering organizations. During the validation of the results with experts, Wärtsilä – global Original Equipment Manufacturer of engines to maritime industry – the managing director mentioned company’s investment in alternative fuel engines, specifically a hybrid fuel engine, that would run using ethanol, methanol as well as diesel, biodiesel and HVO. The company already had its product validated within internal procedures and are now prospecting potential clients for a first order. These innovations are gradually gaining traction and influencing the broader regime. The correlation matrix reveals that internal SPPs like developed goals for sustainable purchasing (DGSP) and measures to develop sustainability-focused purchasing policies (MDPP) are more strongly associated with current sustainability perceptions. This suggests that niche innovations are currently being integrated into mainstream operations, contributing to the regime shift towards sustainability.

The role of the landscape level, encompassing broader societal and environmental trends, is also evident. The industry's focus on fuels, maintenance services, and safety equipment reflects the growing emphasis on energy efficiency and emission reductions, aligning with global sustainability goals. The strong correlations between maintenance-related practices, such as fleet repair and port infrastructure, highlight the interconnected nature of sustainability efforts across different aspects of maritime operations.

For maritime companies considering alternative fuels, the research provides several practical recommendations. Several niche fuels and propulsion technologies are under investigation, and up to the date of the conclusion of this dissertation, it is unclear which will be the fuel or maybe fuels, of the new social-technical regime. Several regime lock-ins support the maintenance of carbon-based fuels, and niche fuels and technologies will need the support of policies and the government to transition to a new operational social-technical regime. The MLP framework offered a valuable perspective on these regime lock-ins and the potential for niche innovations to break through with the support of landscape pressures and policy interventions (Geels, 2002, 2012; Unruh, 2000).

The strength of this study lies in its detailed insight into current practices, providing a clear picture of where companies stand in their sustainability journey. However, the survey's limitations include the potential for response bias and the need for a larger, more diverse sample to generalize findings more effectively. Future research could explore the barriers to adoption and the specific benefits realized by companies leading in sustainable procurement.

Policymakers play a vital role in facilitating the adoption of alternative fuels. Creating supportive regulatory frameworks and providing economic incentives can significantly reduce barriers. International cooperation and alignment of regulatory standards are essential to ensure a cohesive approach to reducing maritime emissions. Policies should focus on mitigating environmental risks and ensuring the safe adoption of alternative fuels through rigorous safety standards and risk management practices. Evidence from MacLeod's analysis indicates that regions with proactive governance and clear regulatory support tend to achieve better environmental outcomes (MacLeod, 2001). However, merely establishing regulations is insufficient; there must also be a focus on mitigating environmental risks through rigorous safety standards and comprehensive risk management practices. This dual approach of stringent regulations combined with practical support mechanisms can significantly lower the barriers to adopting alternative fuels, promoting a cohesive and effective strategy for reducing maritime emissions. This highlights the necessity for policymakers to not only set ambitious environmental targets but also ensure the local adaptability and enforceability of these regulations to drive substantial industry-wide change. The MLP framework underscores the importance of aligning landscape-level policy interventions with niche innovations and regime dynamics to achieve a successful sustainability transition (Geels, 2020).

In light of the established definitions of theory by Wacker (1998) and the contributions from Durach et al. (2021) and Seuring et al. (2021), it is appropriate to consider the work of this dissertation as a meaningful contribution to the expansion of theory within the maritime transition to sustainability. This dissertation delivers a meta-theory combining institutional theory with MLP, extending existing theories, and making a novel application to adopt alternative fuels in the maritime industry, addressing the critical challenge of decarbonization.

The dissertation establishes its ontological basis, and the theories used, defining key terms and constructs, such as alternative fuels, institutional pressures, and decision-making processes within the maritime sector. These definitions provide a solid foundation for the analysis, ensuring that all critical elements are explicitly outlined, fulfilling Wacker's criterion for conceptual definitions.

The dissertation establishes specific domain limitations by focusing on the maritime industry's transition to low-carbon fuels. It delineates the MLP transition on environmental, regulatory, and technological regimes, landscapes and niches where the proposed theory applies, thereby adhering to the criteria for domain limitations. By mapping out these interactions and pressures, the adapted MLP framework, Figure 26, enhanced by Institutional Theory, provides a meta-theoretical contribution to understanding sustainability transitions in complex, regulated industries like maritime transport. This approach not only highlights the multi-faceted nature of such transitions but also showcases the critical role of institutional pressures in shaping and being shaped by technological and operational changes.

The proposed meta-theory effectively illustrates the relationships between institutional pressures and decision-making regarding adopting alternative fuels. It explores how regulatory, normative, and mimetic pressures interact with organizational decision-making processes in MLP's three landscapes, regimes, and niche segments, aligning with Wacker's emphasis on relationship-building in theory development.

The dissertation makes concrete predictions about the increasing adoption of alternative fuels in response to evolving institutional pressures and technological advancements. These predictions are specific and testable, consistent with the empirical riskiness virtue, suggesting that the theory can be empirically validated.

The meta-theory proposed in this dissertation contributes to the expansion of theoretical frameworks in maritime sustainability transition by (i) introducing an unique perspective by integrating institutional theory with MLP sustainability transitions, distinct from traditional approaches in maritime studies; (ii) while comprehensive, the theory remains as simple as necessary to explain the phenomena without undue complexity; (iii) building upon and extending existing theories rather than replacing them, providing new insights and improvements; (iv) although tailored to the maritime industry, the principles could be applicable to other sectors facing similar social-technological regimes and landscapes; (v) opening up numerous avenues for future research, including the exploration of specific institutional strategies and technological innovations migration from niche to regime; (vi) the relationships and constructs within the meta-theory are logically coherent and well-integrated; (vii) the predictive nature of the theory allows for empirical testing and potential falsification through future research, and; (viii) it synthesizes multiple relationships and variables into a comprehensive framework that captures the complexity of MLP of maritime sustainability transitions.

While the dissertation adopts and applies a meta-theory to alternative maritime fuels, it does not offer a novel meta-theory. Still, it is an expansion of the existing MLP meta-theory. The proposed meta-theory enhances the theoretical landscape by offering a robust, applicable, and insightful framework that aids in understanding and facilitating the maritime industry's transition to more sustainable practices. This contribution is theoretical and has practical implications for policymaking and industry practices, underscoring the relevance and utility of the theory in real-world contexts.

Table 14 organizes the key theoretical elements of the research using the Theory Extension approach (Seuring et al., 2020), which is suited for integrating external theories into the study of maritime sustainability. It succinctly captures the definitions, boundaries, variables, causalities, and predictions that frame the research within the broader discourse on sustainability transitions in the maritime sector.

Table 14: Key theoretical elements of the meta-theory.

Element of Theory	Description
Definition (who and what)	Definitions of alternative fuels, institutional pressures, and sustainability transitions are provided. Alternative fuels are defined as those that present a lower net GHG emission than traditional maritime fuels. Institutional pressures include regulatory, normative, and mimetic forces that influence organizational behaviour in the industry. Sustainability transitions occur with the interaction of actors struggling between niches and regimes under external pressures from the landscape. Traditional fossil fuels are excluded.
Boundaries and Limitations (when and where)	The study focuses on the maritime industry's transition to low-carbon fuels. It excludes other modes of transportation and non-fuel-related environmental strategies. The geographical focus is primarily on regions with significant maritime traffic and regulatory frameworks supporting alternative fuel adoption.
Variables and Causalities (why and how)	Variables: Alternative fuels, institutional pressures, decision-making processes, barriers, and enablers. Causalities: The study explores how landscape pressures influence maritime stakeholders' decision-making processes regarding adopting alternative fuels. It also analyses the interplay between technological innovations and regulatory frameworks. Based on MLP, it takes a long-term perspective for the sustainability transition, emphasizing the lock-in mechanisms of the incumbent regime of fossil fuels and the struggle of new entrants from the niches of alternative fuels.
Predictions (could, should and would)	The dissertation predicts an increase in adopting alternative fuels in the maritime sector due to growing institutional pressures and technological advancements. It suggests that future research should focus on technological innovation, policy development, and international cooperation to support further adopting sustainable practices in the maritime industry. Under the lens of MLP, it predicts fierce competition in the niches among several alternative fuels competing to enter the dominant regime.

The dissertation on adopting alternative fuels in the maritime sector aims to enrich maritime sustainability discourse by introducing concepts and frameworks from outside the immediate field of maritime studies. For example, it integrates institutional theory and sustainability transition frameworks, which are not traditionally confined to the maritime sector but are brought in to enhance understanding of the changes in maritime fuel adoption.

By borrowing from broader MLP sustainability and institutional theories, the dissertation extends its theoretical foundation beyond typical maritime-focused studies. This merge of theories offers a new meta-theory, perspectives, and insights into the challenges and opportunities within the maritime industry, thus broadening the theoretical repository available for understanding and addressing these issues.

The dissertation's objectives include evaluating the current state of alternative fuels and the decision-making processes surrounding their adoption in the maritime industry. By integrating external theories (e.g. MLP on sustainability transitions and Institutional Theory), the research provides a richer, more comprehensive view of how these transitions occur, providing hints about how they can be managed and facilitated within the maritime context.

Extending existing theories into new domains enhances the dissertation's relevance and contributes to theory development by testing and applying these theories in new, practical contexts. This theoretical extension ensures that the research is grounded in established theories and innovative in applying them to solve sector-specific problems.

6 Conclusions and Recommendations

This dissertation investigated the adoption of alternative fuels in the maritime industry through a decision analysis lens, guided by the MLP and Institutional Theory. The research aimed to understand the decision-making processes, barriers, enablers, and the influence of institutional pressures on the adoption of sustainable fuels. Key findings include the significant role of coercive, normative, and mimetic pressures, the technological and economic barriers, and the critical enablers such as regulatory frameworks and technological advancements.

The study found that coercive pressures from international and national regulations are pivotal in driving the adoption of alternative fuels. Mimetic pressures from cargo owners and industry best practices, along with normative pressures from safety and compliance standards, also play substantial roles. Technological and economic barriers, including high initial costs and complex regulatory landscapes, hinder adoption. Conversely, supportive regulatory frameworks, economic incentives, and technological advancements act as crucial enablers.

The maritime industry, a vital component of global trade and logistics, faces mounting pressure to reduce its environmental footprint and transition to sustainable fuels. This dissertation seeks to address this critical challenge by exploring the decision-making processes involved in the adoption of alternative fuels within the maritime sector. Central to this investigation are three key research questions: Firstly, *how does the application of decision analysis contribute to sustainable fuel selection processes in the maritime industry (RQ1)?* Secondly, *what are the main research streams of sustainability for the shipping industry, and how have these evolved over time (RQ2)?* Thirdly, *what are the barriers to and enablers of the adoption of sustainable fuels (RQ3)?* Through a sequential exploratory mixed-method approach, this study provided a comprehensive understanding of these questions, offering valuable insights for both academic research and practical implementation in the pursuit of maritime decarbonization.

The dissertation addresses **RQ1** by employing a sequential exploratory mixed-method approach that integrates qualitative and quantitative research methodologies. The qualitative phase gathers in-depth insights into the environmental strategies of the maritime sector, forming the basis for the quantitative phase. This approach allows for a comprehensive analysis of how decision analysis tools like the Multi-Criteria Decision-Making (MCDM), optimization models and others, shown in Table 8 can be effectively used to evaluate sustainable fuel options. The findings demonstrate that decision analysis facilitates a structured and systematic evaluation of alternative fuels, considering various criteria such as cost, environmental impact, and regulatory compliance. The results underscore the utility of decision analysis in aiding stakeholders to make informed and sustainable fuel choices.

RQ2 was answered through the tertiary literature review in Appendix D, the scoping review and a bibliometric study of the literature on maritime sustainability. The scoping review identifies key themes and gaps in the existing research, mapping out the barriers, facilitators, and decision-making processes related to low-carbon fuel adoption. The bibliometric analysis reveals an increasing research focus on alternative low-carbon fuels from 2008 onwards, with significant contributions from leading journals and authors. The study highlights the evolution of research streams, showing a shift towards more comprehensive and integrative approaches to sustainability in the shipping industry. This evolution reflects the growing recognition of the need for holistic solutions to address environmental challenges in maritime transportation.

Finally, the dissertation explored **RQ3** through both qualitative insights and quantitative survey data. The scoping review identifies several barriers, including high initial costs, complex regulatory landscapes, safety concerns, and limited infrastructure. On the other hand, enablers such as technological advancements, economic incentives, supportive regulatory frameworks, and collaborative efforts are also highlighted. The survey results from the Brazilian maritime industry further validate these findings, revealing that coercive, mimetic, and normative pressures significantly influence the adoption of sustainable fuels. The study provides a detailed comparative analysis of these barriers and enablers, offering practical recommendations to address the challenges and leverage the facilitating factors.

The dissertation provides a robust framework for understanding and promoting the transition to sustainable fuels in the maritime industry, contributing to both theoretical knowledge and practical applications.

The findings underscore the importance of institutional pressures in shaping the maritime industry's transition to sustainable fuels. Coercive pressures, particularly from the IMO, are critical in enforcing compliance and driving technological adoption. Mimetic and normative pressures complement these by promoting best practices and ensuring safety and compliance. The study's framework, integrating MLP and Institutional Theory, offers a comprehensive understanding of how these pressures interact and influence decision-making.

This research extends existing knowledge by highlighting the dynamic interplay between regulatory, normative, and mimetic pressures in the maritime industry. It challenges current understandings by showing that technological and economic barriers can be mitigated through collaborative efforts and supportive policies. The integration of qualitative and quantitative methods provides a holistic view of the factors influencing sustainable fuel adoption.

The scope of this study was limited to specific sectors of the maritime industry and may not fully represent the diversity of the entire industry. Geographical constraints also limit the generalizability of the findings, as regulatory environments and market conditions vary significantly across regions.

Methodological limitations include the sample size and data collection methods. While the scoping review provided a comprehensive overview, the reliance on published literature may introduce bias. Future research could benefit from larger sample sizes and more diverse data sources, including primary data collection through interviews and surveys.

Future research could address these limitations by expanding the scope to include more diverse geographical regions and employing longitudinal studies to capture the evolving nature of the industry. Additionally, incorporating more in-depth qualitative interviews could provide richer insights into stakeholder perspectives.

The study recommends that policymakers and industry stakeholders prioritize creating and enforcing supportive regulatory frameworks, e.g. strengthen international and national regulations to enforce compliance with sustainable fuel standards. Economic incentives should be enhanced to offset the high initial costs of adopting alternative fuels, e.g. develop financial mechanisms such as subsidies, grants, and tax incentives to reduce the economic burden on companies adopting alternative fuels. Collaborative efforts among industry players should be encouraged to share best practices and drive technological advancements, e.g. foster industry collaborations to share knowledge and best practices, promoting a collective approach to sustainability. Technological innovation advancement, trough the invest in research and development to advance technological solutions that facilitate the transition to low-carbon fuels.

This research contributes to Institutional Theory by illustrating how coercive, normative, and mimetic pressures collectively influence the adoption of sustainable practices in a global industry. It integrates these insights with the MLP framework, offering a nuanced understanding of how different levels of influence interact in the maritime sector.

The findings provide practical guidance for industry stakeholders, highlighting the importance of regulatory frameworks, economic incentives, and collaborative efforts. The proposed decision-making framework can be used by maritime companies to evaluate alternative fuels comprehensively, considering institutional pressures and practical feasibility.

Future research should explore the long-term impacts of regulatory changes and technological advancements on the adoption of sustainable fuels. There is also a need to investigate the role of stakeholder collaboration in overcoming barriers and leveraging enablers.

Further studies could expand the scope to different regions and sectors within the maritime industry. Employing longitudinal methodologies and more in-depth qualitative approaches can provide a deeper understanding of the evolving dynamics and stakeholder perspectives.

This dissertation provides a comprehensive analysis of the factors influencing the adoption of alternative fuels in the maritime industry. The integration of MLP and Institutional Theory offers valuable insights into the complex decision-making processes. The findings highlight the critical role of institutional pressures and the interplay between technological and economic factors. The practical recommendations and proposed framework provide actionable steps for policymakers and industry stakeholders, contributing to the transition towards sustainable maritime operations. This research underscores the importance of collaborative efforts and supportive policies in achieving sustainability goals, reinforcing the significance of this study for both theoretical advancement and practical application.

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Appendix A: SOBENA survey support

SOBENA
Sociedade Brasileira de Engenharia Naval

PUC RIO

DEI
DEPARTAMENTO
DE ENGENHARIA
INDUSTRIAL

Rio de Janeiro, 30 de janeiro de 2024

Sr. Mário de Luna Barbosa
Gerente Geral de Vendas para a América Latina
Wärtsilä

Prezado Sr. Barbosa,

É com grande estima que me dirijo a você. O propósito desta carta é estender um convite formal para que se junte a nós como um valioso colaborador em uma pesquisa de mestrado que está sendo conduzida sob minha orientação pelo Sr. Felipe Dutra.

O tema central da pesquisa é a "Adoção de Biocombustíveis na Navegação" e reconhecemos que sua expertise e experiência profissional, especialmente na sua função como Gerente Geral de Vendas para a América Latina na Wärtsilä, seriam de imenso valor. O propósito deste convite é solicitar sua valiosa colaboração nos seguintes aspectos:

1. Participar como ouvinte e parecerista na banca de qualificação do mestrado.
2. Contribuir para a pesquisa sobre compras sustentáveis no setor de navegação.
3. Conceder uma entrevista abordando aspectos específicos dos biocombustíveis na navegação.

Sua experiência no setor de energia, particularmente com relação à inovação e sustentabilidade em soluções de energia para a navegação, será de grande relevância para a pesquisa. Esperamos que sua participação enriqueça o trabalho acadêmico e contribua para as práticas sustentáveis no setor marítimo.

Ficaríamos honrados com a sua aceitação e estamos disponíveis para discutir como sua participação pode ser mais efetiva e proveitosa. Pedimos a gentileza de uma resposta até 07-fevereiro, para que possamos organizar adequadamente sua participação.

Agradeço antecipadamente por considerar este convite e fico à disposição para quaisquer esclarecimentos adicionais.

Atenciosamente,

Prof. Márcio Thomé,
Orientador de Pesquisa
DEI - PUC-Rio

Felipe Dutra
Pesquisador de Mestrado
DEI - PUC-Rio

Departamento de Engenharia Industrial
Rua Marquês de São Vicente, 225 – 9º andar, Prédio Cardeal Leme
Gávea – Rio de Janeiro – 22.451-900 | Tel. (55 21) 3527-1286
www.ind.puc-rio.br

DEI
DEPARTAMENTO
DE ENGENHARIA
INDUSTRIAL

Rio de Janeiro, 30 de janeiro de 2024

Sr. Raphael Piccelli
Gerente de Engenharia e Inovação
Hidrovias do Brasil

Prezado Sr. Piccelli,

É com grande estima que me dirijo a você. O propósito desta carta é estender um convite formal para que se junte a nós como um valioso colaborador em uma pesquisa de mestrado que está sendo conduzida sob minha orientação pelo Felipe Dutra.

O tema central da pesquisa é a "Adoção de Biocombustíveis na Navegação". Dada a sua notável experiência e conhecimento profundo neste campo, especialmente em sua capacidade como Gerente de Engenharia e Inovação na empresa Hidrovias do Brasil, acreditamos que sua contribuição será imensurável.

Especificamente, gostaríamos de convidá-lo para:

1. Participar como ouvinte e parecerista na banca de qualificação do mestrado.
2. Colaborar na pesquisa relacionada a compras sustentáveis para a navegação.
3. Conceder uma entrevista focada no uso de biocombustíveis na navegação.

Acreditamos que sua experiência prática e perspectiva no setor de biocombustíveis agregará um valor inestimável à pesquisa, enriquecendo tanto a qualidade acadêmica quanto a aplicabilidade prática dos resultados.

Estamos ansiosos para colaborar com você e acredito firmemente que sua participação será um marco significativo neste projeto. Em anexo, encontrará mais detalhes sobre a pesquisa.

Por favor, não hesite em nos contatar para discutir sua possível participação ou para esclarecer quaisquer dúvidas. Sua resposta até o dia 07-fevereiro para resposta será muito apreciada para facilitar os preparativos.

Atenciosamente,

Prof. Márcio Thomé,
Orientador de Pesquisa
DEI - PUC-Rio

Felipe Dutra
Pesquisador de Mestrado
DEI - PUC-Rio

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Appendix B: Statistical test result

Statistical Test Used

The assessment of internal validity based on the timing of survey responses was conducted using the Wilcoxon Rank-Sum test. This non-parametric statistical test is suitable for comparing differences between two independent samples when the dependent variable is ordinal or continuous but not normally distributed. The dataset was divided into two groups based on survey completion times: before and after the median date. This division allowed for comparison across various survey variables.

Implementation of the Test in R

The statistical analysis was implemented in the R programming language. The Wilcoxon Rank-Sum test was applied to several numerical variables in the dataset to detect any significant differences in responses that could be attributed to when the survey was completed.

R Environment and Package Details

To ensure the reproducibility of this analysis, details of the R environment and packages used are provided below:

- R Version: 4.3.2 (2023-10-31)
- Platform: aarch64-apple-darwin20, 64-bit
- Running under: macOS Sonoma 14.5

Key R Packages Used:

- dplyr (1.1.4): Data manipulation
- ggplot2 (3.5.0): Data visualization
- tidyverse (2.0.0): An umbrella package that includes dplyr and ggplot2 among others for data analysis
- lubridate (1.9.3): Date and time manipulation

These packages were instrumental in processing and analysing the dataset, ensuring that all statistical tests were performed accurately.

Results

The Wilcoxon test results for each variable were as follows:

- Sustainability Today: p-value = 0.6807
- Sustainability Future: p-value = 0.8410
- Fuels: p-value = 0.6358

- Spare Parts: p-value = 0.9145
- Safety Equipment: p-value = 0.5240
- Maintenance: p-value = 0.8460
- IT Equipment: p-value = 0.2015
- Fleet Repair: p-value = 0.2467
- Dredging: p-value = 0.3537
- Port Infrastructure: p-value = 0.8980
- Office Supplies: p-value = 0.5967
- Communications Equipment: p-value = 0.7000
- Reputation: p-value = 0.8883
- Ethics: p-value = 0.6101
- Best Practices: p-value = 0.7316
- Future Legislation: p-value = 0.8991
- Current Legislation: p-value = 0.2811
- CEO's Perspective: p-value = 0.6747
- Cost Saving: p-value = 0.8398
- Client Relations: p-value = 0.6274
- Third-party Relations: p-value = 0.1152

Interpretation of Results

The analysis demonstrated no significant differences in responses before and after the median survey date across all variables tested (all p-values > 0.05). This suggests robust internal validity concerning the timing of responses, indicating that external factors, respondent fatigue, or shifts in societal attitudes did not significantly influence survey results. This appendix confirms the reliability of the data, supporting its use for further detailed analyses in the main body of this thesis.

Appendix C: Interview script

Interview Script
Company and respondent profile 1. Can you please introduce yourself and describe your role within the company? Justification: This helps establish the respondent's position, responsibilities, and level of influence regarding strategic decisions, particularly those related to fleet operations and environmental practices. 2. Could you provide a brief overview of your company, including the size of your fleet, types of vessels operated, and main operational regions? Justification: Understanding the scale and scope of the company's operations provides context for their capacity to adopt new technologies and fuels, and highlights any regional considerations that might affect their choices. 3. What is the current fuel mix or technology base used in your fleet? Justification: This question assesses the current state of the fleet's technology and fuel usage, setting a baseline for discussions about potential changes and improvements. 4. Has your company previously implemented any significant technological upgrades or shifts in fuel usage? If so, can you detail these changes? Justification: Insights into past initiatives and their outcomes can indicate the company's experience and readiness for future transitions, as well as their historical commitment to innovation and sustainability. 5. What are your company's primary strategic goals for the next five to ten years? Justification: This question aligns the conversation with the company's long-term strategic planning, providing a backdrop against which their interest in alternative fuels and new technologies can be assessed. 6. Which markets does your company primarily serve, and how do these markets influence your operational and environmental strategies? Justification: Understanding the specific markets (e.g., regional, global, specific cargo types) the company targets can reveal how market demands and characteristics influence their decisions on fuels and technologies, including environmental considerations. 7. Has your company established any specific goals regarding the reduction of carbon emissions? If so, can you elaborate on these targets and your strategies to achieve them? Justification: This question gauges the company's commitment to environmental stewardship and helps identify whether their sustainability goals align with global or industry-specific emissions reduction targets. It also provides insight into the company's response to environmental regulations and market expectations. Specific questions regarding alternative fuels adoption

Interview Script
1. What are your primary motivations for considering alternative fuels or technologies in your fleet? Justification: Understanding the strategic drivers (e.g., environmental concerns, regulatory compliance, cost savings, etc) behind the shift provides insight into the company’s priorities and helps tailor solutions that align with global sustainability goals. 2. Which alternative fuels or technologies are you currently evaluating, and what are the expected environmental benefits of these options? Justification: This question gathers specific information on the types of fuels or technologies considered and the anticipated environmental impact, aligning with broader sustainability objectives. 3. How do you assess the economic impact of transitioning to these alternatives, including both initial investment and operational costs? Justification: Understanding the economic feasibility is crucial for financial planning and evaluating the long-term viability of the investment, including any cost savings or financial incentives. 4. What technological adaptations or infrastructure upgrades are required to implement these new fuels or technologies in your existing fleet? Justification: Addresses technical feasibility and readiness, essential for understanding the scope of changes needed and any potential barriers to implementation. 5. How do you manage the risks and safety considerations associated with new fuels or technologies? Justification: Safety and risk management are paramount, and this question seeks to understand measures taken to mitigate risks related to new fuels, such as flammability, toxicity, or operational hazards. 6. Can you describe any pilot projects or trials you've undertaken with these new options? What have been the outcomes? Justification: Inquiring about pilot projects provides insights into experimental or early adoption experiences, revealing practical outcomes and lessons learned. 7. What major challenges and barriers do you anticipate or have already encountered in adopting these new technologies or fuels? Justification: Identifying challenges helps in understanding practical obstacles, supply chain issues, or regulatory hurdles, providing insights into areas that need strategic solutions. 8. What role do regulatory requirements and environmental policies play in your decisions to adopt these new technologies? Justification: This probes the extent to which regulatory frameworks and policies shape the company's strategies, reflecting compliance-driven motivations and environmental stewardship.

Interview Script
9. How do you engage with stakeholders (e.g., crew, cargo owners, regulatory bodies) in the decision-making process? Justification: This explores the social and organizational aspects of decision-making, highlighting the importance of stakeholder engagement in facilitating a smooth transition. 10. Looking ahead, how do you perceive the future of fuel use and technology in the maritime industry, and what kind of support or changes at the policy level would assist you in transitioning more effectively? Justification: Asking about future perspectives and needed policy support reveals the company's long-term strategic planning and highlights areas where industry advocacy might be necessary.

Appendix D: Tertiary literature review

Provided in a separate file.