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Future Fuels: A Serious Game Analysis of Port and Ship-owner Decision-Making in Maritime Decarbonization

by

Giuditta Schmidt (699763)

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Abstract

The maritime industry faces an urgent need to meet global climate targets, yet the pathway to decarbonization remains uncertain. This thesis explores how the initiator (ports or shipowners) of fuel transition efforts influences the success of maritime decarbonization strategies. Employing the serious game PortConstructor "Future Fuels", designed to simulate complex trade-offs between operational efficiency, profitability, and environmental impact, a mixed-methods approach was applied. Five test sessions involving participants from maritime and related sectors examined port-led and shipowner-led transition scenarios under different stakeholder interaction conditions. Quantitative game data was enriched with qualitative insights from expert interviews to validate results and evaluate serious games as a research tool. Findings show that frequent, well-structured stakeholder dialogue enhances strategic alignment across People, Profit, and Planet goals, with coordination and information sharing essential to success. Port-led transitions leveraged infrastructure control but risked reactive decisions, while shipowner-led transitions enabled clearer long-term planning but were limited by infrastructure availability. The thesis concludes that effective decarbonization requires integrated decision-making, strong communication, and iterative learning, and that serious games offer a valuable platform to simulate and understand these complex dynamics.

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List of Abbreviations

CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator
CSR	Corporate Social Responsibility
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
GSC	Green Shipping Corridor
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
IMO	International Maritime Organization
KVNR	Koninlijke Vereniging van Nederlandse Reders (Royal Association of Netherlands Shipowners)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MOU	Memorandum of Understanding
NGO	Non-Government Organization
NOx	Nitrogen Oxides
OPS	Onshore Power Supply
SCR	Selective Catalytic Reduction
SOLAS	International Convention for the Safety of Life at Sea
STC	Shipping and Transport College (Rotterdam)
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978
SVO	Straight Vegetable Oil
UNCTAD	United Nations Conference on Trade and Development
USA	United States of America
VLSFO	Very Low Sulphur Fuel Oil
WAPS	Wind Assisted Propulsion System

1. Introduction

1.1. Background

Shipping is responsible for nearly 3 % of global greenhouse gas (GHG) emissions, making alignment with the Paris Agreement's 1.5°C target urgent. The industry faces a pressing challenge to move away from fossil fuels, with ports and shipowners playing crucial roles. Growing decarbonization commitments and tighter regulations have made fleet renewal and greener vessels top priorities. However, the future of marine fuels remains uncertain. Key regulations like the European Union's (EU) Emissions Trading System (ETS) and the International Maritime Organization's (IMO) Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), are driving change. Meeting these standards requires investments in new ships, retrofitting existing ones, and scrapping older vessels. Retrofitting, though, can reduce cargo capacity due to constraints on vessel weight and space. Dual-fuel vessels, especially Liquefied Natural Gas (LNG) and methanol-powered ships, now dominate new orders, with increasing interest in ammonia-capable ships and LNG as a transition fuel. Wind-assisted propulsion and shore-side power are also being explored. Ports are expanding infrastructure for alternative fuels and adopting environmental management standards (UNCTAD, 2024; UNCTAD, 2023).

In 2023, the IMO adopted a new GHG strategy aiming for at least a 20 % emissions reduction by 2030 (targeting 30 %), a 70 % cut by 2040 (targeting 80 %), and net-zero around 2050, all compared to 2008 levels. Immediate measures like the EEXI and CII influence ship speed, value, earnings, and capacity, while mid-term policies under development include a goal-based fuel standard and emissions pricing. Despite progress, almost 99 % of the fleet still uses conventional fuels, though 21 % of vessels on order are designed for alternatives such as LNG, Liquefied Petroleum Gas (LPG), battery/hybrid, and methanol. Substantial emission reductions will depend on scaling advanced biofuels, e-fuels like methanol and ammonia, and hydrogen, requiring major investments in production and distribution infrastructure beyond shipping alone (UNCTAD, 2023).

Fleet carbon intensity reductions have stalled, but total emissions rose 4.7 % from 2020 to 2021 due to rebounding maritime activity and limited efficiency gains. Container ships and bulk cargo vessels improved their carbon intensity, but tankers lag, influenced by size, speed, and fleet makeup. Larger ships are generally more efficient. New IMO rules encourage slow steaming and retrofitting. However, regulatory uncertainty, high costs, and long ship lifespans hinder investments in greener vessels. Concerns about environmental assessment tools for scrapping persist. Low investment in environmental projects and workforce training, especially for decarbonization and digitalization, remain a barrier. Ports remain essential enablers by offering alternative fuel bunkering and adopting environmental management systems (UNCTAD, 2022; UNCTAD, 2024).

Choosing suitable alternative fuels is crucial. Biofuels have limitations, methanol and ethanol are promising transition fuels, ammonia offers a zero-carbon option, and hydrogen may be a future fuel with a phased approach (Herdzik, 2021). Trade-offs exist between energy efficiency, cost, and emissions. Fossil fuels with carbon capture are a cost-effective short-term option, while biofuels balance cost, availability, and readiness (Law et al., 2021). E-fuels offer over 85 % potential emission reductions with policies and renewable energy, while biofuels can reduce emissions up to 78 %, but sustainability and efficiency of biomass remain a concern (Kanchiralla, Brynolf, & Mjelde, 2024). Renewable methanol is feasible but hindered by cost, and choice depends on context, especially for developing countries (Svanberg et al., 2018; Munim et al., 2023). Calls for banning fossil fuels by 2050 stress the need for clearer policies and faster action, possibly requiring governance reforms and unilateral actions (van Leeuwen & Monios, 2022).

Finance for the transition is concentrated among a few financiers aware of risks and opportunities, shaping investment flows. Hydrogen may be cost-effective under some conditions, and LNG may prevail where bunkering infrastructure is expensive (Fricaudet, Parker, & Rehmatulla, 2023; Jesus et al., 2024). Ports deploy technical and operational incentives but need harmonized global frameworks for fair competition (Alamoush, Ölçer, & Ballini, 2022). Alternative fuels face economic, technical, regulatory, and infrastructural barriers, including low production volumes, transport and bunkering gaps, lower energy density, and safety challenges. Higher upfront costs prevail, although LNG and LPG may offer long-term savings given price volatility (Foretich et al., 2021; Harahap, Samavati, & Nurdiawati, 2023).

In summary, decarbonization is propelled by regulation-led fleet renewal and innovation, but technological, infrastructure, and financing uncertainties hinder investment. Ports are key enablers yet face funding and skills challenges. The maritime energy transition demands coordinated commitment, strategies, and investment across the sector for a sustainable future.

1.2. Research Question, Sub-Research Questions, and Objectives

This thesis will try to answer the following research question:

How does the initiator of fuel transition decisions (port vs. shipowner) impact the success of decarbonization efforts in the maritime industry?

The sub-research questions are the following:

1. What are the current maritime decarbonization challenges faced by ports and shipowners?
2. What are key factors influencing the effectiveness of port-led vs. shipowner-led approaches in selecting and implementing alternative fuel strategies?
3. How do the interactions between ports and shipowners in a serious game simulation compare to real-world decision-making processes in the maritime fuel transition?

1.3. Research Design and Methodology

For this thesis, a mixed method approach is used. Data of a serious game is used to analyze different stakeholder behaviors with regards to implementing fuel transition strategies in the shipping industry. The stakeholders investigated are ports and shipowners. In different set-ups of the game, different situations will be simulated, e.g., how often the stakeholders interact with each other. The collected data will then be complemented by conducting interviews with industry experts. These interviews shall also help with validating the results of the analysis of the game data.

1.4. Structure of the Thesis

This thesis is structured as follows: First an extensive literature review will be conducted to depict the current maritime decarbonization landscape, the policy and legal framework, the port and shipowner dynamics in the fuel transition, and the data collection method using a serious game. Next, the methodology will be explained. In this chapter an overview of the design of the serious game PortConstructor "Future Fuels", the data collection methods, and validation will be given. The fourth chapter will be dedicated to the results and analysis. The game outcome will be analyzed, both from a port-led transition scenario as well as from a shipowner-led transition scenario. These two outcomes will then undergo a comparative analysis. The results will be complemented and validated through expert interviews. At the end of the chapter the game results will be integrated with industry perspectives. The last chapter of the thesis will be the conclusion. Here, the key findings will be used to answer the research questions, and limitations of the study will be presented. Additionally, suggestions for future research will be given.

2. Literature Review

2.1. Maritime Decarbonization Landscape

Despite several advances, the shipping sector faces persistent challenges. The fleet's carbon intensity decline has plateaued. Meanwhile, total emissions rose by 4.7 % between 2020 and 2021, largely due to a rebound in maritime activity combined with only modest energy efficiency gains. Container ships and bulk/general cargo vessels have made notable progress in reducing carbon intensity over the past decade, but tankers have lagged. This disparity is influenced by factors such as ship size, slow steaming, and fleet composition. Generally, larger ships tend to be more efficient. New IMO regulations are expected to further encourage speed reductions and retrofitting, but investment in greener vessels and fuels is hindered by regulatory uncertainty, high costs, and the long lifespan of ships. Concerns persist regarding the adequacy of environmental assessment tools for scrapping activities. Additionally, investment in environmental projects and workforce training for decarbonization and digitalization remains low. The effectiveness of new IMO regulations depends on increased awareness among all stakeholders, including transport users, and ongoing investment in technology and workforce training. Ports are critical enablers of the energy transition, offering alternative fuel bunkering infrastructure and adopting environmental management systems (UNCTAD, 2022).

The UNCTAD 2024 Review of Maritime Transport (2024) highlights that growing decarbonization commitments and regulatory measures are making global fleet renewal a central issue for the shipping industry. The fuels of the future remain uncertain, but the regulatory landscape is becoming more stringent in response to climate change. Key measures include the EU's ETS and compliance with IMO requirements such as the EEXI and the CII, both of which became mandatory in 2023. The industry's transition to low-carbon fuels and stricter environmental regulations is a major driver for change, necessitating the adoption of newer, greener, and more efficient vessels. This transition involves investments in newbuilds, retrofitting existing vessels, and scrapping older tonnage. While retrofitting existing vessels is a viable solution, it reduces available cargo capacity due to the vessel's weight and space constraints. The ordering of dual-fuel vessels has increased, with these ships making up most of the container ship capacity on order at the start of 2024. Some of these vessels are ammonia-capable, and there is a growing interest in LNG. Other technologies under consideration include wind-assisted propulsion and shore-side power. The shipbuilding sector is under pressure, as its capacity will affect the timely renewal of the global fleet and the pace of decarbonization. Regulations such as the IMO CII and EU ETS affect operational factors including sailing speeds. This may result in less energy-efficient ships operating at reduced speeds to lower overall emissions and absorb fleet overcapacity. Although younger, greener fleets are becoming available, concerns remain about whether environmental assessment tools for activities such as scrapping are adequate (UNCTAD, 2024).

The search for the right alternative fuel is central to the shipping industry's decarbonization efforts. Herdzik (2021) examined various alternatives including biofuels, methanol, ethanol, ammonia, and hydrogen. He concluded that biofuels have limitations, methanol and ethanol are potential transition fuels, ammonia is a promising zero-carbon option, and hydrogen could be a future fuel, although with a gradual transition.

Similarly, Law et al. (2021) compared 22 alternative fuel pathways and found trade-offs between energy efficiency, cost, and emissions. Fossil fuel with carbon capture storage (CCS) offers a cost-effective, energy-efficient short-term solution, while biofuels present a compromise in terms of cost, availability, and technological readiness.

Kanchiralla, Brynolf, and Mjelde (2024) found that e-fuels have the highest climate mitigation potential, with reductions of more than 85 % compared to traditional fuels, provided there is significant policy support and investment in renewable energy infrastructure. Biofuels can reduce emissions by up to 78 %, but concerns exist regarding the sustainability of biomass sources and the efficiency of gasification processes.

Svanberg et al. (2018) identified renewable methanol as a technically feasible option to reduce shipping emissions, although economic factors hinder its widespread adoption. Munim et al. (2023) suggest a multi-criteria decision-making approach to assess alternative energy sources, noting that the fuel choice depends on the context, with developing countries facing unique challenges in adopting alternatives.

Van Leeuwen and Monios (2022) advocate for a more radical approach, proposing a complete ban of fossil fuels by 2050. They argue for clear policy signals, and a shortened timeline. They also highlight flaws in the IMO's governance, suggesting that unilateral action may be necessary to drive change.

From a finance perspective, Fricaudet, Parker, and Rehmatulla (2023) found that the shipping debt market is dominated by a small number of financiers whose behavior is influenced by their awareness of risks and opportunities associated with the fuel transition. These financiers aim to support established shipowners in the transition by adapting financial tools and instruments.

Jesus et al. (2024) analyzed the cost-effectiveness of different fuels using a framework that accounts for bunkering, lost cargo capacity, vessel conversion, and carbon taxes. They concluded that hydrogen could be the most cost-effective option under certain conditions, while LNG may be more economical when bunkering infrastructure costs are high.

Alamoush, Ölçer, and Ballini (2022) examined port measures and found that common port incentive schemes are facilitating the decarbonization of shipping. They argue that a mix of technical and operational measures, implemented by both ships and ports along with policy tools, is needed for a successful transition. A harmonized global incentive scheme is emphasized to create a level playing field among ports.

Harahap, Samavati, and Nurdiawati (2023) also stress the importance of transitioning to alternative fuels, noting that the optimal choice depends on specific contexts and that current regulations are insufficient. Economic and technical barriers continue to delay the widespread adoption of alternative fuels.

Despite the potential offered by alternative fuels, significant challenges remain. Foretich et al. (2021) reviewed and evaluated twelve marine fuel pathways, including conventional fuels (Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Heavy Fuel Oil (HFO)) and alternatives (LPG, LNG, methanol, Straight Vegetable Oil (SVO), Hydrotreated Vegetable Oil (HVO), biodiesel, biocrude, bio-oils, ammonia, hydrogen), and identified key obstacles. Infrastructure for production, transportation, combustion, and bunkering are lacking and require expansion. Production volumes are insufficient, and fuel quality standards for some biofuels are not established. Many alternatives have a lower energy density than HFO, necessitating larger tanks. Additionally, some biofuels (except HVO) have stability issues. Other concerns include cold weather performance, material compatibility (such as ammonia's corrosiveness), and engine compatibility, with some fuels requiring dual-fuel engines or modifications. Economically, alternative fuels are generally more expensive, and require major capital investments for infrastructure and retrofits, although LNG/LPG may offer lower long-term costs but are subject to price volatility. Safety concerns also vary, with toxicity, flammability, and spill risks differing by fuel type. For example, methanol and ammonia are toxic, while LNG/LPG present greater flammability and explosion risks (Foretich et al., 2021).

In summary, the shipping sector continues to face significant challenges despite advances, with emissions rising and carbon intensity improvements leveling off. Regulatory measures are driving fleet renewal and adoption of alternative fuels, yet uncertainties around technology, infrastructure, and costs hinder widespread investments. Ports play a crucial enabling role, but low investment in environmental management and workforce training underscores the complexity of achieving a successful energy transition.

2.2. Policy and Legal Framework

The transition must be just and equitable, particularly for developing countries, the least developed countries, and small island developing states. Economic measures proposed by the IMO, potentially generating funds to support these economies, invest in climate-resilient port infrastructure, and facilitate trade and transport reforms (UNCTAD, 2024; UNCTAD, 2023; UNCTAD, 2022).

Policy recommendations emphasize the need for:

- Clear regulations and targets for zero or near-zero fuels,
- Support for research and development, promotion of multi-fuel ship designs,
- Leveraging digital tools, and fostering partnerships,
- Establishing green corridors, ensuring a level playing field,
- Providing technical and financial support to developing countries

(UNCTAD, 2024; UNCTAD, 2023; UNCTAD, 2022).

Within this complex regulatory and environmental landscape, Corporate Social Responsibility (CSR), which involves voluntary initiatives by companies to address social and environmental impacts, has emerged as an important strategy for shipping companies to address increasing environmental and social pressures. Kitada and Ölçer (2015) note that although shipping is more energy efficient per ton nautical mile than other transport modes, it still significantly contributes to global CO_2 emissions. The industry faces growing pressure to improve its environmental performance, driven by international agreements such as the Kyoto Protocol, regulations like MARPOL Annex VI (International Convention for the Prevention of Pollution from Ships), the finite nature of fossil fuels, rising energy demand, volatile fuel prices, and the need for energy security. Energy efficiency is thus a cornerstone of sustainable maritime transportation. Some large shipping companies have integrated Corporate Social Responsibility (CSR) at both strategic and operational levels, framing it through the “triple bottom line” of People (social aspect), Planet (environment), and Profit (results). In the context of energy efficiency, environmental concerns (Planet) and cost savings (Profit) are primary drivers, whereas the People aspect (social consideration) is often overlooked or insufficiently integrated (Kitada & Ölçer, 2015).

The human element is critical for both selecting and implementing energy efficiency measures. Decision-making is complex and involves multiple criteria, including cost, performance, safety, and trade-offs. Effective implementation requires adequate knowledge and training. However, seafarers may lack awareness, knowledge, motivation, or sufficient training. Organizational and behavioral barriers can arise, especially when there is a disconnect between shore-based managers and onboard crew, or when the crew is excluded from the decision-making processes. Additionally, psychological barriers may also emerge in the absence of open dialogue between managers and workers. Moreover, transferring corporate ideology into daily practice is challenging, as managers must embed the vision for energy efficiency and CSR into employees' routines and mindsets. This complexity is heightened by the need to manage both people and technology across diverse regulatory and organizational contexts. This is especially challenging for multinational corporations with limited direct control over their supply chains. Managers must also balance economic objectives with stakeholder interests. Kitada and Ölçer (2015) caution against over-reliance on CSR to fill regulatory gaps, particularly in areas lacking public scrutiny or robust standards, such as seafarers' welfare. Instead they advocate for a balanced approach that combines regulatory compliance with CSR. They strongly support an interdisciplinary strategy that connects technical, socio-economic, and human factors (Kitada & Ölçer, 2015).

The environmental impacts of shipping, air emissions, oil and chemical discharges, waste, and invasive species, are severe. The main international regulatory framework, primarily set by the IMO (MARPOL, International Convention for the Safety of Life at Sea (SOLAS), International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 (STCW)), has been criticized for being slow, ineffective, and lacking clear enforcement. As a result, voluntary CSR practices have been explored to improve safety and reduce environmental impact. While CSR is well-established in some land-based industries, its adoption in shipping remains limited, and its benefits are not always clear to companies. The highly competitive and globalized nature of shipping encourages a focus on short-term profit, whereas CSR often generates long-term value. Implementation is further complicated by geographical and regulatory diversity. Moreover, while environmental issues receive varying attention across sectors, social issues are often neglected. Concerns about CSR being used as 'greenwashing' persist. Parvianinen et al. (2017) argue that stakeholder participation is essential for realizing the full societal benefits of CSR. Historically, the shipping industry has operated as a business-to-business sector, with limited influence from non-financial stakeholders such as Non-Government Organizations (NGOs), media, or consumers. However, there is a growing recognition of the need for broader stakeholder involvement in maritime governance. 'Stakeholder Theory' is used to analyze how both primary (formal relationships, e.g., shareholders, customers, governments) and secondary (informal, e.g., NGOs, media, citizens) stakeholders can drive CSR adoption. Influence strategies can be direct or indirect, involving conditions on providing resources or withholding resources. Multi-stakeholder dialogue and alliances, among industry, consumers, NGOs, regulators, and others, can apply pressure to adopt greater social and environmental responsibility, increase transparency and legitimacy, aid enforcement, broaden the sustainability discourse, and ultimately drive regulatory improvements (Parvianinen et al., 2017).

In summary, the maritime transition must ensure equity, especially for developing and vulnerabel countries, through taregeted economic support, clear regulations, and collaborative policies. Corporate Social Responsibility complements regulations by addressing environmental and social challenges, though effective implementation requires overcoming human, organizational, and stakeholder engagement barriers within a complex global contex.

2.3. Port and Shipowner Dynamics in Fuel Transition

Ports are increasingly recognized as crucial players in the global energy transition. They are moving beyond their traditional role as cargo handling hubs to become vital interfaces between maritime transport and land-based supply chains (Bielenia, Marusic, and Dumanska, 2024). Ports are transforming into multifunctional energy platforms that integrate transport, transformation, and energy generation, thus playing a central role in the broader decarbonization of global energy systems. As a result, port strategies must be reevaluated to prioritize energy efficiency and environmental performance, aligning closely with the decarbonization objectives of the maritime sector (Bielenia, Marusic, & Dumanska, 2024).

The integration of ports into Green Shipping Corridors (GSCs) is fundamental to achieving the IMO's GHG emission reduction targets. Ports provide essential infrastructure such as alternative fuel bunkering and safety protocols, which are critical for the transition to zero-emission shipping. However, this transition faces several challenges, including limited stakeholder collaboration, especially with shipping companies, constraints in alternative fuel availability, and high investment costs in green technologies. Additional barriers include insufficient government involvement, immature technologies, and operational network rigidity. Ismail et al. (2024) propose a structured eight-stage implementation plan for ports that includes stages such as awareness building, challenge identification, government engagement, securing funding, stakeholder collaboration, and infrastructure planning. The final stages involve developing financial strategies, launching pilot projects, and implementing continuous monitoring. This comprehensive framework is designed to guide ports through the intricacies of integrating into GSCs and advancing maritime decarbonization (Ismail et al., 2024).

The role of actors’ resources, capabilities, and strategies is also crucial in driving the energy transition. Strong intermediaries, such as the Port of Oslo, can facilitate the development of producer, legitimator, and consumer roles, thereby foster innovation and reduce risks (Bjerkan, Ryghaug, and Skjosvold, 2022).

Explicit local and national policies are essential to empower these intermediaries and ensure an effective transition (Bjerkan, Ryghaug, and Skjosvold, 2022). In addition, Dirzka (2024) emphasizes that the transition requires changes in port governance, business models, and stakeholder relationships. He also highlights the importance of considering the social dimensions of the energy transition. He advocates for a system approach to address the complexities associated with the fuel transition in shipping.

Ports can leverage their diverse functions as landlords, operators, authorities, and community members to enable technological deployment, foster collaboration, and drive institutional change. However, the strategic approaches adopted by ports can vary depending on local markets, social networks, and policy frameworks from the IMO and EU. Exogenous pressure is often necessary to disrupt existing regimes and compel ports to adapt (Damman and Steen, 2021).

Klopott, Popek, and Urbanyi-Popiolek (2023) concur that seaports are central to the energy transition, providing critical bunkering infrastructure for alternative fuels such as LNG, methanol, hydrogen, and ammonia. Despite this, ports face significant challenges related to fuel availability, cost, and environmental compatibility, necessitating cross-sector collaboration and proactive planning.

Sornn-Friese (2024) further advocates for interdisciplinary and transdisciplinary approaches to fully understand the role of ports as energy transition hubs.

Ship-owners are also key decision-makers in the transition process. Pilot projects are highlighted as essential for overcoming market entry barriers and accelerating the energy transition in the shipping sector, which is characterized by a cluster of sub-regimes with varying characteristics, making a uniform transition challenging (Stolper, Bergsma, and Pruyn, 2022).

Research among early adopters in Norway reveals that large, established companies with newer fleets in profitable segments are more likely to adopt alternative fuels, driven by profitability, competitive advantage, and public image. In contrast, smaller ship-owners with older fleets, particularly in coastal fisheries, lag due to financial and informational barriers. Contractual demands and public procurement policies, especially for passenger ferries, are effective in accelerating the adoption of alternative fuels, illustrating the impact of market-pull drivers. To scale up biofuels and meet emission targets, subsidies and feed-in targets are essential (Mäkitie et al., 2022).

Underlying the effectiveness of both regulatory and voluntary initiatives are the motivations of individuals and organizations. Motivation can be intrinsic, where actions are performed for their own sake because they are enjoyable or interesting, or extrinsic, where actions are taken to achieve a separate outcome, such as rewards or the avoidance of punishment. Extrinsic motivation exists on a continuum, from external regulation (controlled by external forces) through introjected, identified, and integrated regulation, the latter being most autonomous but still serving external values or identity rather than pure enjoyment (Legult, 2016).

In the context of shipping, both intrinsic and extrinsic motivations shape how individuals and organizations respond to environmental and social pressures.

Culture also plays a decisive role in shaping motivation. Markus (2016) argues that while Western cultures often emphasize self-regulation, where actions are driven by internal needs and values, in much of the world, motivation is shaped by other-regulation, fulfilling expectations and duties rooted in relationships and social norms. This distinction is crucial in a global industry like shipping, where diverse cultural backgrounds influence how motivation is experienced and expressed. Referencing others, fulfilling duties, and maintaining social standing can be associated with positive outcomes, and understanding these cultural dynamics is essential for designing effective policies and CSR strategies (Markus, 2016).

Jones (1999) offers a detailed critique of rational choice theory as a descriptive model of decision-making, arguing that empirical findings across behavioral decision theory, organization studies, and experimental economics consistently demonstrate its limitations. He advances the concept of bounded rationality, positioning individuals as intendedly rational, goal-oriented and adaptive, but constrained by cognitive and emotional limitations. These constraints lead to a mismatch between decision-making environments and actual behavior, which Jones (1999) terms "bounded rationality showing through". He distinguishes between procedural limits (e.g. attention, emotion) and substantive limits (e.g. tendencies like over-cooperation) that affect how decisions are made and their outcomes. Building on previous work, Jones (1999) describes a decision-making process where people settle for a good enough option rather than trying to find the optimal one, due to limited cognitive and environmental complexity. He challenges traditional models by showing that decisions are influenced by incomplete information, emotions, and changing contexts. He also argues that effective models must consider these factors along with traits like impulsivity and shifting preferences.

Henderson (1981) draws a clear distinction between contrived and non-contrived environments for management teacher development, focusing on how learning occurs rather than how teaching is delivered. While contrived learning experiences, such as formal training courses, induction programs, and conferences, were designed explicitly for development, they were often perceived as offering limited value, particularly by less experienced teachers. Gains such as improved planning or insights into learner relationships were acknowledged but frequently considered too abstract or only subconsciously absorbed. In contrast, non-contrived learning experiences, which arose incidentally through personal, professional, and social contexts, were identified as the most powerful stimuli for development. These included work experience, consultancy, reflection prompted by discussion or reading, observation of others, and even negative learning from poor educational encounters. Such experiences fostered deep learning by prompting adaptation, self-awareness, and belief formation about the teaching-learning process. Although slower and sometimes challenging, non-contrived learning was considered richer and more authentic. Henderson (1981) advocates for a blended approach where contrived opportunities are used strategically to deepen and accelerate learning from non-contrived experiences.

A 'wicked problem' is complex, ambiguous, and without definitive solutions, thereby requiring a fundamental rethinking of how learning and decision-making are approached. Unlike ‘tame' or ‘complicated-complex' problems, which can be approached through single-loop (“Are we doing things right?”) or double-loop (“Are we doing the right things?”) learning, wicked problems necessitate triple-loop learning: the most advanced and transformative form of learning. Triple-loop learning demands a fundamental shift in thinking, and seeks to answer the deeper question, “Are we doing the right things right?”. This approach goes beyond adjusting or reframing existing knowledge to uncover the underlying dynamics of cause and effect (van Tulder & van Mil, 2023).

Crucially, triple-loop learning embraces a high tolerance of ambiguity, encourages reflective and paradoxical thinking, and promotes “outside-the-box” thinking, enabling longer-term vision and shared value creation. Rather than aiming for fixed solutions, it supports continuous adjustment in the face of persistent uncertainty. In this sense, learning becomes an ongoing, iterative process of adaptation, aligned with the inherent nature of wicked problems (van Tulder & van Mil, 2023).

In summary, ports are emerging as multifaceted energy platforms that facilitate decarbonization through infrastructure development and stakeholder collaboration. Shipowners face diverse challenges influenced by fleet composition, financial constraints, and market pressure, necessitating pilot projects and supportive policies to accelerate alternative fuel adoption. Decision-making in this complex setting is shaped by both intrinsic and extrinsic motivations, cultural contexts, and bounded rationality, where actors often satisfice under cognitive and environmental limitations. The transition constitutes a ‘wicked problem’, characterized by ambiguity and evolving challenges, requiring triple-loop learning that fosters reflective, adaptive, and innovative thinking beyond conventional solutions. This holistic approach emphasizes continuous learning, systemic adaptation, and shared value creation, enabling the maritime sector to navigate uncertainty and achieve decarbonization goals. Ultimately, success depends on integrated strategies combining technological innovation, governance reforms, and socio-cultural understanding across all stakeholders.

2.4. Serious Games as a research method

Serious games have established themselves as a significant and rapidly growing field of study. A bibliometric analysis by Cifrci (2018), covering the years 2007 to 2017, demonstrates a steady increase in research activity related to serious games. This growth underscores the field’s interdisciplinary relevance and the expanding interest from both researchers and developers worldwide. The field’s interdisciplinary nature is evident in the application of serious games across domains such as educational technology, psychology, healthcare, and business (Cifrci, 2018).

Mayer et al. (2013) propose a conceptual framework breaking down the gaming process into stages such as pre-game preparation, the quality of the intervention itself, and post-game follow-up, all influenced by contextual factors like player demographics and environment. They recommend the use of quasi-experimental designs for rigorous evaluation and highlight the importance of mixed-method data collection, integrating surveys, observations, and in-game data, to achieve triangulation and enhance research validity.

Debriefing is another fundamental component of simulation games, fostering learning through structured reflection and knowledge transfer (Roungas et al., 2018; Roungas et al., 2021). However, the effectiveness of debriefing can be compromised by factors such as inadequate facilitator involvement, poor planning, limited time, and gaps in emotional safety (Roungas et al., 2018). Expert opinions highlight the critical roles in ensuring successful debriefing sessions (Roungas et al., 2018).

Usability testing in serious games, as analyzed by Moreno-Ger et al. (2012), requires a tailored approach that extends beyond traditional metrics like efficiency and error reduction. Instead, it must also account for learning, engagement, and enjoyment. Their methodology involves analyzing recorded gameplay with multiple reviewers, allowing for early identification of usability issues during the design process.

Serious games also offer innovative opportunities for data collection. For example, Verloop (2018) explored the use of a serious game to gather data on food waste behaviors, addressing the shortcomings of conventional methods such as surveys and diaries. In his study, players managed food with real-life considerations like price and freshness. Although the initial version of the game had limitations, its data collection system successfully captured player actions, demonstrating serious games' potential for refining behavioral data reliability (Verloop, 2018).

Despite these advances, several challenges persist in the field. Mayer et al. (2013) point to fragmentation within serious game research, which hinders unified knowledge accumulation and comparative evaluation. Similarly, Verloop (2018) recommends further refinements to improve the reliability of serious games as data collection tools.

Simulation games, a subset of serious games, offer unique advantages for understanding complex socio-technical systems, such as seaports. Bekebrede and Mayer (2006) note that simulation games allow users to experience the long-term consequences of their decisions in a safe and accelerated environment. These games can incorporate technical, social, and economic factors, enabling participants to engage in strategic, and sometimes irrational, behaviors that mirror real-world dynamics (Bekebrede and Meijer, 2009). By simulating scenarios involving diverse stakeholders and interconnected components, simulation games help participants grasp emergent behaviors and unintended outcomes that are typical of complex systems (Bekebrede and Mayer, 2006).

A notable example is the SimPort framework, a multiplayer management game platform designed to meet the specific needs of the serious game industry. SimPort supports multiplayer sessions, manages network communication, and offers an extendable structure for developers. Its application in SimMV2, a model simulating the Maasvlakte 2 expansion of the Port of Rotterdam, demonstrated the framework's effectiveness in educational and professional contexts, improving communication and facilitating real-life learning through game-based experiences (Warmerdam et al., 2006).

Simulation games serve as powerful learning tools by enabling active, engaging experiences that overcome bounded rationality and promote innovative decision-making. They simulate complex socio-technical systems, facilitate interaction among diverse stakeholders, and foster shared perspectives, negotiation, and collective decision-making. By representing real systems through rules, roles, and resources, these games support training, strategy development, and knowledge transfer. Their alignment with experiential learning principles, including active engagement, receiving immediate feedback, and reflective practice, makes simulation games especially effective (Jansen, Bekebrede, & van Houwelingen).

PortConstructor 2.0, developed based on the SimPort framework, was designed to address the lack of evaluation concerning learning, engagement, and motivation in port simulator games. It was created in response to increasing complexity in port planning, driven by technological advancement, growing port competition, and the demands of governments and civil society. Social dilemmas, such as coastal protection vs. port expansion, housing vs. air pollution, jobs vs. automation, and fossil vs. renewable energy, add further complexity, alongside challenges like space allocation, economic development, automated terminals, energy transition, and diverse stakeholder demands (Jansen, Bekebrede, & van Houwelingen).

The study by Jansen, Bekebrede, and van Houwelingen investigates whether simulation games can help address these complexities. Specifically, it explores the effect of game embedding on knowledge, motivation, activation, and engagement. The research evaluates knowledge gain about port challenges, the activation of learning in related material, and the enhancement of motivation and engagement. PortConstructor 2.0 includes two missions: the Hinterland mission, which focuses on sustainable hinterland transport, and the Anyport mission, which addresses the strategic shift toward sustainable ports.

Findings indicate that players gained meaningful insights into the complexities of port design, especially in balancing "People, Planet, and Profit". Game embeddedness significantly influenced game outcomes. The Hinterland mission, integrated more deeply into lectures, assignments, and debriefing, resulted in better outcomes and fostered more active learning than the more standalone Anyport mission. The game also facilitated reflection and effectively connected the simulation to real-world port contexts (Jansen, Bekebrede, & van Houwelingen).

Importantly, the results show no significant difference in learning outcomes between students and professionals. Overall, the study concludes that simulation and serious games are valuable tools for learning in the context of complex port planning and social dilemmas (Jansen, Bekebrede, & van Houwelingen).

In summary, serious games have rapidly grown as interdisciplinary tools applied across education, psychology, healthcare, and business, offering innovative approaches for learning and data collection. Simulation games, a subtype of serious games, enable users to explore complex socio-technical systems like ports by simulating decision-making, stakeholder interactions, and emergent behaviors in an engaging, reflective environment. Platforms like the SimPort framework and PortConstructor 2.0 demonstrate the effectiveness of game-based learning for addressing real-world port planning complexities, enhancing knowledge, motivation, and engagement among both students and professionals. The research highlights that deeper integration of games within curricula fosters more active learning and meaningful reflection, supporting the use of serious games as valuable tools in managing complex challenges.

3. Methodology

3.1. Conceptual Framework and Data Collection

3.1.1. Conceptual Framework

The goal of these experiments is to identify factors influencing decision-making in maritime decarbonization. To simplify the experiments, only two stakeholders are considered: ports and shipowners. An important part of these experiments are the stakeholder discussions, during which the two groups exchange information and potentially develop a shared strategy. It is assumed that stakeholder discussions improve the quality of outcomes, not necessarily accelerating the transition speed, but rather enhancing how well the transition balances key objectives. The effectiveness of the outcomes is measured by how well participants balance People, Profit, and Planet. We will document the frequency and timing of stakeholder discussions and ask participants to list the three key points raised during each discussion.

PortConstructor 2.0[1] is a serious game composed of micro-games focused on port design, providing insights originally related to port management and spatial planning.

Building on PortConstructor 2.0, a new mission called "Future Fuels" was developed.

Game performance is measured by how well the three indicators – People, Profit, Planet – are balanced.

- "People" represents the efficiency and effectiveness of operational processes both on ships and within the port. For example, a process scores 100 % when the fuel supplied by bunkering and storage matches the fleet's fuel demand exactly.
- "Profit" represents the revenues generated. The ships generate profit by transporting cargo in the game. The higher the profits, the higher the score.
- "Planet" measures environmental impact, and is negatively affected by the use of polluting fuels such as Very Low Sulphur Fuel Oil (VLSFO) and CO_2 emissions. Transitioning to sustainable fuels and technologies improves the Planet score.

[1] For the game mission, the game Port Constructor developed by TUDelft, EUR UPT, Port of Rotterdam, STC, and InThere was used as a basis.

The game simulates the complex interplay of certain factors in the fuel transition. Players must respond to a changing cargo market by expanding their fleets to meet demand, while facing financial constraints and limited alternative fuel availability. Players must evaluate the costs of various fuel options and vessel types, as each vessel's cost depends on its fuel source. Additionally, some fuels become available only later in the game, reflecting their level of technological readiness.[2]

Players are divided into groups representing ports and shipowners to simulate stakeholder dynamics. Through dialogue, they exchange strategies and ideas in an effort to find common ground for maritime decarbonization. Stakeholder dialogues are used for information exchange and potential strategy adaptation. To evaluate the impact of these stakeholder discussions, testing sessions vary: some include no discussions; others feature one discussion at the beginning, in the middle, or both. Each discussion lasts five to ten minutes.

Policy instruments, such as carbon pricing implemented as a cost per unit of CO_2 emitted, are incorporated in the game and are designed to influence vessel and fuel choices.

Similar to reality, participants must navigate trade-offs among cost, efficiency, and environmental impact.

3.1.2. Data Collection

For data collection, a questionnaire was designed. At the beginning of each testing session, participants are informed that they will complete the questionnaire after the debriefing but before the session ends, ensuring the content remains present and participants are still in the mindset of their assigned stakeholder role.

The questionnaire includes a range of questions designed to provide an overview of participants' decision-making processes throughout the game. It begins with general questions about the gaming session and the participants' background and knowledge to establish context, followed by requests for participants to describe and explain their strategic choices, and concludes with evaluations of those choices' effectiveness. The full questionnaire is provided in Appendix 1.

Ideally, the research subjects are professionals from the shipowner and port industry, as the game targets their decision-making processes. However, due to limited access, proxy groups with sufficient knowledge on the topic were used to make informed judgments. As noted by Jansen, Bekebrede, and van Houwelingen, using proxy groups is a common practice when using

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[2] see Appendix 2 for a detailed overview of the cargo market and availability of fuels

serious games as research tools. Though, this approach may lead to decisions that do not achieve the best possible outcomes.

To ensure participants understand their stakeholder roles, they receive a handout defining their stakeholder type and describing their roles in both the maritime decarbonization process and the game. Participant immersion will be evaluated based on questionnaire responses and observations during the test sessions. Immersion refers to the extent to which participants embodied their assigned stakeholder roles and engaged actively in gameplay and discussions both within and between stakeholder groups. Immersion will be measured immediately after the testing session concludes. Observations begin when the timer starts for the initial strategy discussion prior to gameplay. Facilitators manage the session environment by physically dividing the room, timing activities, and signaling when participants transition to subsequent steps.

3.2. Serious Game Design, limitations in possible decisions

3.2.1. Game Information

The game consists of four interconnected segments:

1. the cargo market, featuring bulk cargo storage and loading facilities,
2. the fuel market, including fuel storage and bunkering facilities for each fuel type,
3. technology options such as Wind-Assisted Propulsion Systems (WAPS) and CCS, applicable for retrofitting existing and new vessels or equipping new builds,
4. CO_2 emissions and captured CO_2 metrics.

These segments interact closely with the fleet of ships. The figure below illustrates the interactions between the different segments within the game.

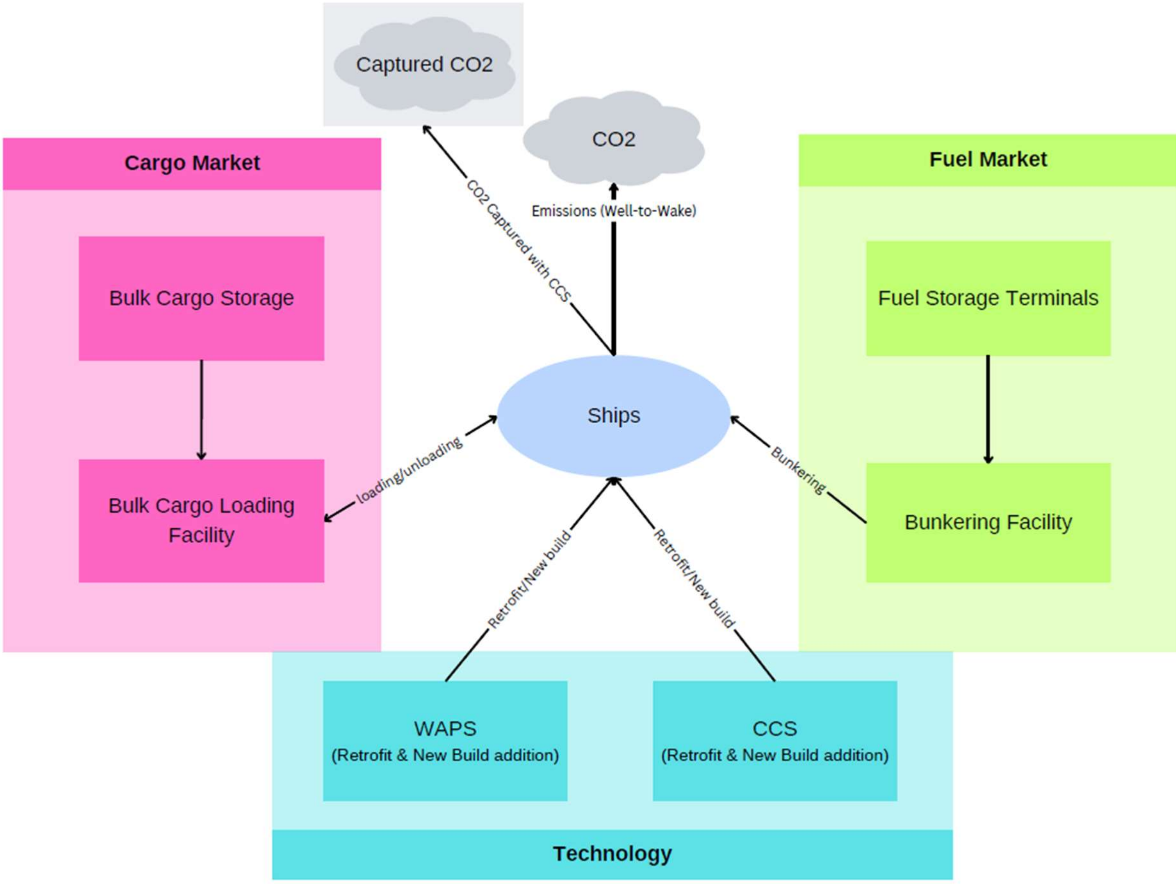

Figure 1 Game dynamics (own work)

The game includes eight vessel classes operating on four fuels: VLSFO, LNG, Methanol, and Ammonia. Although vessel names are fictional, their specifications are based on real-world ships. For a detailed overview of the different vessel types, see Table 1 below.

Vessel Class	Fuel Type	Total Cargo Carried	Average Fuel Consumption (kg/nm)	Total Fuel Consumption (tons)	CO_2 Emissions per ton of fuel burned	Average CO_2 Emissions (kg/nm)	Total CO_2 Emissions (tons)
OCEAN Alex	VLSFO	72,000	51.41	4,300	3.2	163.34	13,500
OCEAN Beatrix	VLSFO	40,000	42.41	3,200	3.2	135.36	10,000
OCEAN Charlotte	VLSFO	24,000	69.55	3,700	3.2	221.21	12,000
OCEAN Diana	LNG	48,000	52.36	4,300	3.1	156.77	13,200
OCEAN Elisabeth	LNG	40,000	51.17	3,800	3.0	153.31	11,300
OCEAN Fiona	LNG	16,400	50.17	2,700	3.0	148.20	7,900

OCEAN Meta	Methanol	66,000	126.84	10,426	2.1	263.08	21,625
OCEAN Anna	Ammonia	56,000	268.52	29,000	N/A	N/A	N/A

Table 1 Vessel Class Overview (compiled based on real-world ships)

Each vessel (existing and new) can be retrofitted with WAPS and/or CCS, or new vessels can be built with these technologies pre-installed. WAPS reduces fuel consumption by 10 %, which directly translates into a 10 % reduction in CO_2 emissions. CCS achieves a 50 % reduction in CO_2 emissions. A vessel can have at most one WAPS and one CCS system installed.

Bunkering and storage infrastructure is provided for each fuel type in the game. For simplification, all vessels carry the same cargo, non-specific dry bulk cargo. The cargo market grows in each round. Availability of VLSFO decreases over time, while alternative fuels see increased availability (see Appendix 2).

Players start with a fleet of 15 VLSFO-powered vessels: six OCEAN Alex, six OCEAN Beatrix, and three OCEAN Charlotte, supported by sufficient VLSFO bunkering and storage infrastructure. These vessels are able to carry all the cargo available in Round 1. Players receive a "Calculation Assistant", a document designed to support strategic decision-making by automating calculations. The calculation sheet is divided into two parts, one for the port infrastructure, the other for the vessels and technologies.

Prior to the game session, players receive preparatory materials, including a presentation on the current state of the energy transition in shipping and handouts such as game guidelines, fact sheets on the regulatory framework, alternative fuels, green shipping corridors, a glossary, stakeholder role descriptions, function overviews for both port and shipowner roles, a vessel class overview, market overviews (fuel, cargo, allowable CO_2 emissions), Calculation Assistant, and the questionnaire.

In Round 4, an incident occurs, affecting the cargo market: due to increasing geopolitical tensions, cargo demand drops by 10 %.

The mission in the game is to reduce CO_2 emissions while maintaining high profits and operational efficiency. CO_2 reductions can be achieved by replacing the initial fleet of 15 VLSFO-powered vessels and associated infrastructure with alternative fuels or retrofitting existing ships. Profits are generated by transporting all available cargo, which requires fleet expansion.

3.2.2. Set-up and execution

We, as facilitators, engage with participants in several ways:

1. At the start of the testing session, participants receive an overview of the process and a brief explanation of the game. They are informed that they will complete a questionnaire at the end of the session.
2. During gameplay, facilitators do not interact with participants except to answer questions related to game mechanics.
3. After gameplay, a debriefing session invites participants to share thoughts, feedback, and elaborate on their experiences.
4. Finally, participants complete the questionnaire.

The set-up of the testing sessions is as follows:

1. Participants will ideally receive the background information on the game and the topic before the testing day to give them the opportunity to familiarize themselves with the material.
2. The room is divided to create physical distance between stakeholder groups, as follows:

Figure 2 Room Set-up

3. The participants will receive additional teaching materials.
4. The participants are divided into two groups, representing the port and the shipowners respectively.
5. Stakeholder roles for the port, shipowner, and facilitator are clearly defined.
   a. Port:
      As a port, the goal is to start/support the decarbonization of the shipping industry. This is done by providing the necessary infrastructure (bunkering and storage facilities). In a port-led transition, port players decide first on infrastructure provisions, with shipowners reacting. In contrast, in a shipowner-led transition, shipowners select fuel strategies first. However, they cannot build vessels powered by alternative fuels unless the corresponding port infrastructure exists.

During the stakeholder discussions, they can try to convince the ship-owner side of their strategy. The budget for the first round is at full disposal of the port. Decarbonization is achieved by replacing VLSFO with more environmentally friendly fuels. One bunkering/storage tile meets the fuel consumption of one ship. Each vessel class has its own set of functions for bunkering/storage. Ships generate profits by carrying cargo, while fuel consumption and CO_2 emissions generate costs (shown as negative profits). Installing WAPS and CCS reduces fuel use and emissions, generating positive profit effects.

b. Shipowner:

As a shipowner, the goal is to decarbonize the fleet, while making sure there is enough capacity to carry all the cargo available on the market. It is also important to keep an eye on fuel availability in the market. In a shipowner-led transition, the players representing the shipowner get to decide the strategy. Depending on the reaction of the port-side, it might be necessary to adapt the strategy. During the stakeholder discussions, they can try to convince the port side of their strategy. The budget for the first round is at full disposal of the shipowner. In a port-led transition, the port decides on the fuel strategy by providing the necessary infrastructure. Building vessels, for which the fuel is not available will reduce the 'People' score. No decisions can be made by shipowners during the first round. The current fleet will need to be extended in order to meet market demand. Decarbonization can be achieved either by replacing existing vessels with new vessels fueled with greener fuels, or by retrofitting vessels with WAPS and/or CCS. New vessels can also be built with a combination of WAPS and/or CCS already installed, meaning there is no need to retrofit them. All vessel classes can be retrofitted with at most one CCS and one WAPS per ship. Profits are generated by ships carrying cargo, while fuel and CO_2 incur costs (represented by negative profits in the game). WAPS and CCS create fuel and CO_2 savings (represented by positive profits in the game).

c. Facilitator:

The facilitator does not intervene in the game and decision-making process. They are responsible for explaining the game at the beginning and making sure all participants understand the process. Depending on the set-up, the facilitator initiates the stakeholder discussions and ensures that parties do not communicate outside scheduled discussions to maintain the integrity of the experiment. The facilitator may answer any questions from the participants, without intervening in their decision-making process. The facilitator is also responsible for time-keeping. In case the group is small, the facilitator may be responsible for combining the decisions from both parties into a common playing field.

6. The facilitator announces which stakeholder group will make the first move.
7. Stakeholder discussions, initiated by the facilitator, occur before and/or during gameplay depending on the session design. These discussions serve solely to exchange information and to attempt to convince the opposing side of one's strategy or collaboratively develop a new strategy.
8. After gameplay concludes, a short debrief allows participants to share feedback, experiences, and learning outcomes.
9. The debriefing includes completion of the questionnaire while memories are still present, ensuring good response quality.

Players have a limited amount of time: five to ten minutes for stakeholder discussion, and for each round. The facilitator manages timekeeping. Early rounds may take longer to help participants become familiar with the game, with subsequent rounds generally requiring less time. Decisions are limited, as the game simulates a simplified version of reality and therefore cannot represent all stakeholders or factors influencing decision-making in fuel transitions. Players select from a limited set of alternative fuels, which may simplify strategic complexity. The game does not account for specific geopolitical developments or policy changes. Retrofitting options are restricted to WAPS and CCS. Changing vessel engines to operate on different fuel types is not possible.

3.3. Validation of the Game Results

Result validation is achieved through interviews with industry experts who bring diverse perspectives from academia, port authorities, shipowner associations, and port advisory bodies. These interviews serve a dual purpose: first, to validate the outcomes obtained from the testing sessions of the serious game PortConstructor; and second, to evaluate the utility of serious games as a data collection and educational tool that aids stakeholders in understanding and navigating complex maritime decarbonization challenges. Importantly, the interviewees do not participate in playing the game themselves, which preserves an analytical distance. They are provided with a concise introduction to the game's objectives, mechanics, and application context, enabling them to critically assess its relevance and effectiveness without direct gameplay experience. This approach ensures that the validation process incorporates informed, objective feedback grounded in industry expertise.

4. Results and Analysis

This chapter shows the results followed by an in-depth analysis.

It is important to note that the data was collected during game testing, and that the game was iteratively modified in response to participants' feedback and learning outcomes throughout the process.

To collect the data, five test sessions of the game were conducted. The groups were chosen as proxies for port and shipping industry professionals because of their assumed industry knowledge about the industry.

Test Date	Group	No. Participants	Background of Participants
16.05.2025	KVNR	4	Shipping Professionals, Dutch Shipowner Association
21.05.2025	Summer School Estonia	12	PhD Students (maritime, sustainability)
26.05.2025	STC Students	14	Logistics Students
05.06.2025	STC Teachers	8	Teachers (ports, logistics, maritime)
10.06. – 13.06.2025	Ports in Transition Elective	4	Master Students (Course: Ports in Transition)

Table 2 Test Session Overview (self-compiled)

4.1. Learning Outcomes and Adaptations

4.1.1. KVNR

The game functions well, as one party must wait to see the other's decisions. The downside, however, is that there are not many options in terms of fuel strategy. It is positive that shipowners cannot simply scrap and replace fleets arbitrarily. It would be better if the supply of ammonia and methanol increased sooner to allow different fuel options. After receiving this feedback, we changed the numbers for the ammonia and methanol market, making it available sooner in the game. Costs on the port side relate solely to infrastructure changes, making it clear, from a shipowner's perspective, that the port plays a leading role. It was found that cooperation is key to a successful transition. Lastly, the participants noted uncertainty regarding budgets due to expensive options.

4.1.2. PhD Class TalTech (Estonia)

In this testing session we tried working with a single laptop, which worked well for the game dynamics. Taking turns adds value, as the participants are curious about what happened during the other stakeholder's turn. This also means that sometimes they are surprised by the fact that the other group used up the entire budget or took too much time. One team did not realize that both storage and bunkering facilities were needed, as the colors were too similar. This was later adjusted. The calculation assistant works well as a supporting document. However, it is difficult to keep up with all groups if there is only a single facilitator. As the strategy phase before beginning the game takes up most of the time and it usually takes a couple of rounds to understand the game, it is difficult to play all ten rounds of the game. In this session six rounds were played. It was suggested by the participants to add CCS facilities to the port side and not just the shipping side, as the ships need to get rid of the CO_2. Adding CCS facilities on the port side was considered, but rejected to avoid increasing the game's complexity, contrary to its aim of simplifying the transition. The players are, however, informed that it is assumed that the CO_2 is discharged and sold in the port, giving a small profit per unit of CO_2 captured. Overall, it can be said that the participants were very engaged and active. They also seemed to have a considerable knowledge about fuel technologies and maritime practices.

4.1.3. STC Students

This test session could have benefited from a more detailed introduction to fuel technologies and maritime practices, as participants lacked sufficient knowledge to fully understand the game. This test group consisted of eight students from Shipping and Transport College (STC) and eight exchange students from the United States of America (USA). This game gave them an opportunity to get to know each other and turned out to be a great opportunity for team building. Again, the time constraint posed a challenge and only five rounds were played. Even if the participants did not have sufficient knowledge of the matter at hand, they enjoyed the dynamics of decision-making and how the different aspects of the fuel transition were integrated.

4.1.4. STC Teachers

Before this test session, the game was shortened to a total of six rounds, and the disruptive event was moved to Round 4. This group also commented that the port does not play a role in terms of CCS, and that the game could benefit from an additional function. Additionally, as the port is not involved in retrofitting vessels with WAPS, this makes planning more volatile and dependent on wind. It also got clear that, even though the calculation assistant adds value as a support document, it is not straight forward enough. Following suggestions, improvements were made. The group also suggested having multiple groups representing the shipowners, but only one group representing the port, as this is also the case in real life. Multiple shipping lines call the same port. The teachers mentioned that from a teaching perspective, it is necessary to play the game multiple times to draw conclusions and to learn the consequences of different strategies. This, however, is not possible during the test sessions. For future use of the game in a seminar setting, it is possible, and suggested, that the participants play multiple times.

4.1.5. Seminar: Ports in Transition

The last test session that was conducted as a seminar with students. The first class consisted of an introduction to the topic of decarbonization in the maritime industry and the distribution of the access code to the game. In the second class, the group was divided into two teams who played the game. During the last class, each group had to give a short presentation about their learning outcomes and reflection on their strategies.

The port side mentioned that their strategy was chaotic and were not able to properly describe it, as they were constantly switching between fuels. Their strategy was incoherent as they tried to adapt to current events at the last minute. However, one participant played individually, outside the group session, prior to presenting. They followed an equal strategy with the port and the shipping side, and ships were equipped with WAPS and CCS. Overall, the group was more reactive to current events rather than being future oriented.

The shipping side, on the other hand, followed a very clear strategy, ammonia and retrofitting. They were more future oriented. In the presentation, they also mentioned that using Selective Catalytic Reduction (SCR) to capture Nitrogen Oxides (NOx) from ammonia vessels would make it even more environmentally friendly.

As a learning outcome the participants posed an interesting question. Maybe this is not a chicken and egg problem, after all? Eventually, all involved stakeholders follow the same goal, decarbonizing the maritime industry.

General feedback included a challenge in developing a strategy, due to limited time. Some participants had trouble figuring out the excel sheet, which led to the addition of a handout explaining in detail how it works in the teaching materials. Generally, the participants would have preferred having more time to play the game, as most of the available time was spent on understanding the workings of the game.

4.2. Game Outcomes

This chapter will present the outcomes of the game. First, the general results will be presented by explaining the answers to the closed questions of the questionnaire. After that, the answers to the open questions will be presented. This will be done to show the development throughout the game. The open answers are also used for the comparison of the different strategies in the following section.

4.2.1. General

As mentioned in the previous chapter, the participants were asked to fill out a questionnaire. 28 of the participants answered almost all the questions. The results of this were as follows:
It is important to note that most participants, approximately 48 %, do not have a maritime background. About 37 % have a background in shipping. The remaining 15 % have a background in related fields such as logistics and academia. Figure 3 illustrates the detailed distribution of participant backgrounds.

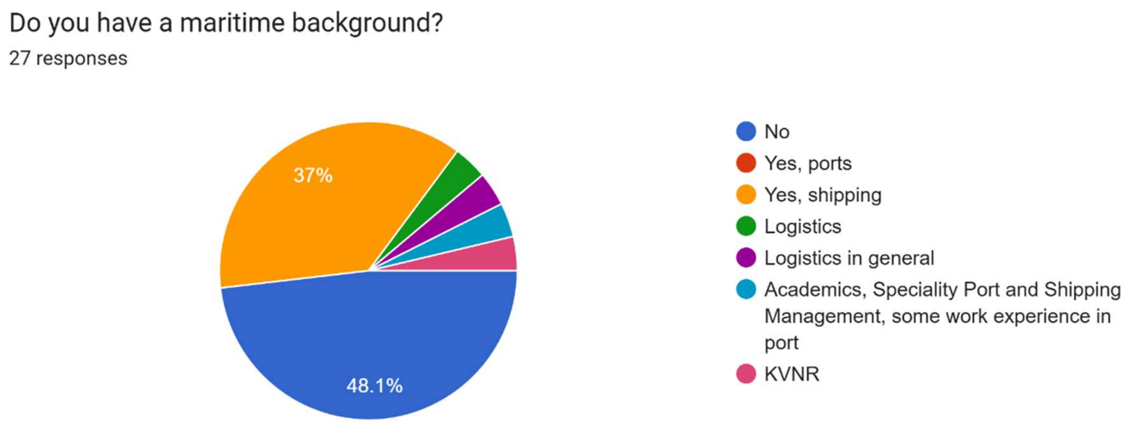

Figure 3 Participants' Background (own work)

In order to achieve comparable results, we tried creating equally sized groups for the two stakeholders, port and shipping. This distribution is reflected in participants' reported stakeholder roles (see Figure 4).

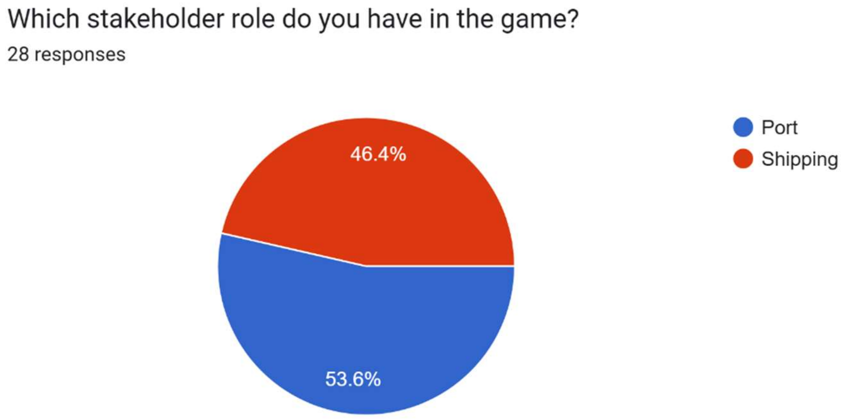

Figure 4 Stakeholder Roles during Test Sessions (own work)

Despite almost equal stakeholder representation, the port side predominantly assumed leadership in the transition process (see Figure 5).

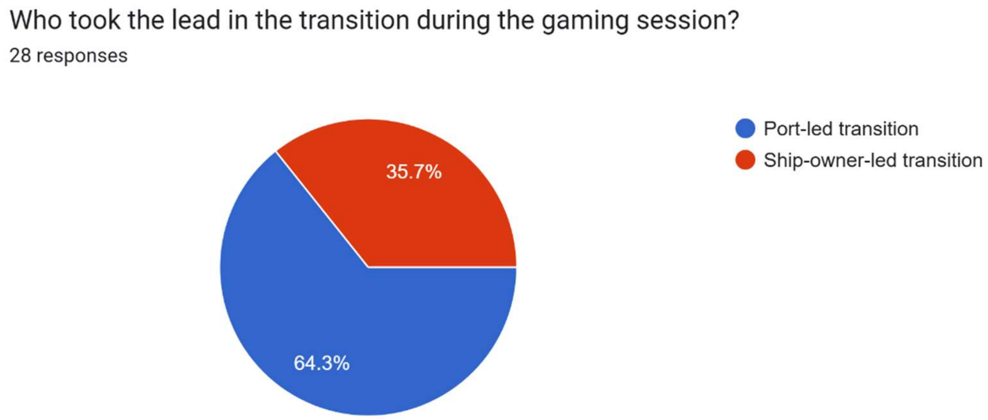

Figure 5 Transition Lead (own work)

Figure 6 illustrates participants' initial fuel strategy choices, formulated during team discussion prior to cross-stakeholder dialogue. At this point, most groups had yet to engage in discussions with the opposing stakeholder group. LNG and Methanol were the most frequently selected fuels.

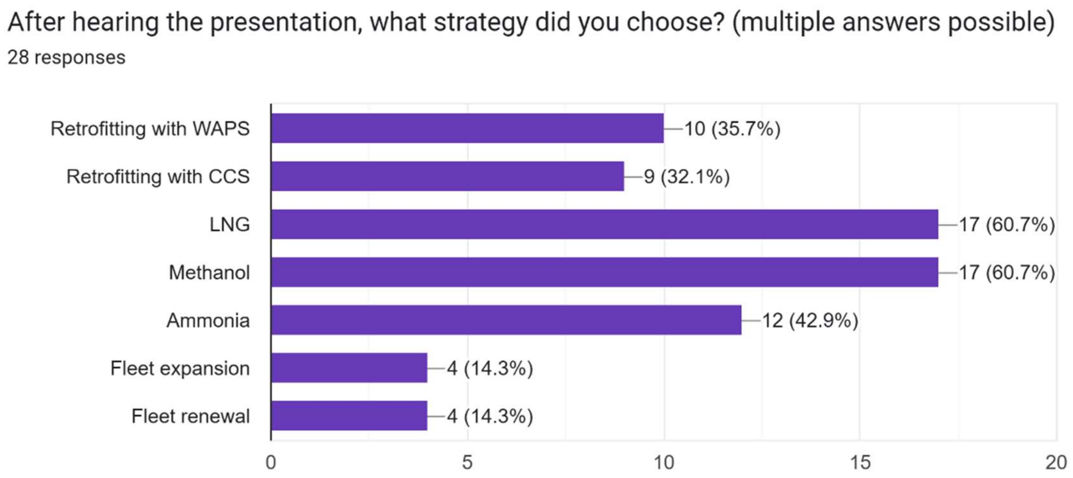

Figure 6 1st Strategies (own work)

After stakeholder discussions, participants reevaluated and adapted their strategies. Figure 7 shows a notable increase in fleet renewal strategies alongside a decline in LNG and Methanol use, with retrofitting becoming more prominent. Overall, strategy diversity increased.

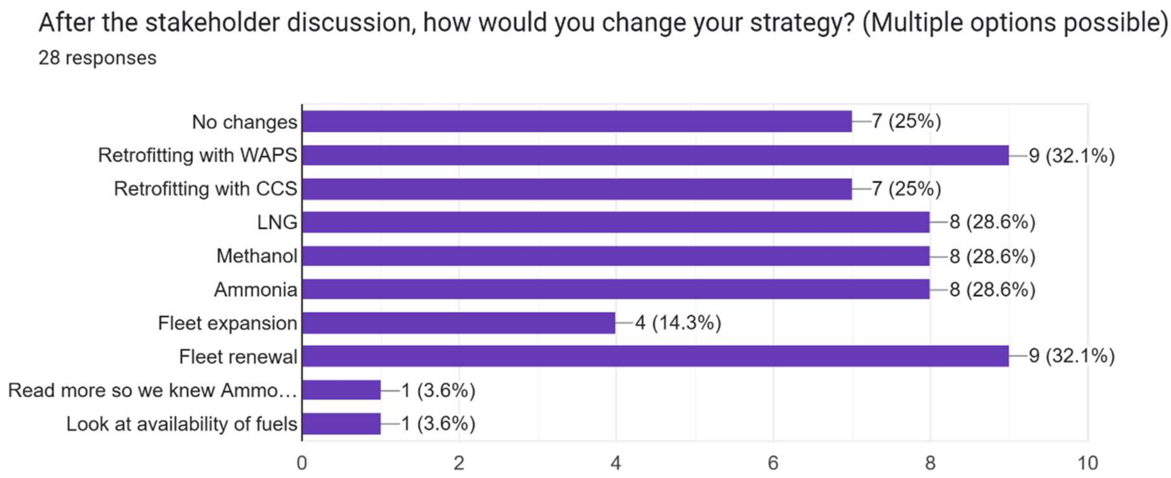

Figure 7 New Strategies (own work)

To evaluate how the frequency of stakeholder discussions influences strategic choices and their effectiveness, testing sessions were conducted with varying numbers of discussions. Figure 8 summarizes these configurations.

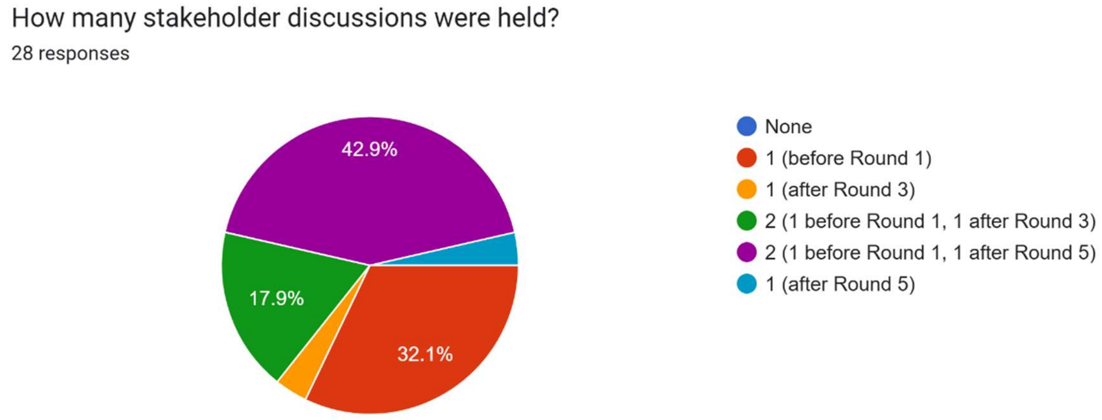

Figure 8 Stakeholder Discussions Overview (own work)

At the end, participants rated the perceived success of their strategies, with most expressing confidence in their effectiveness (Figure 9).

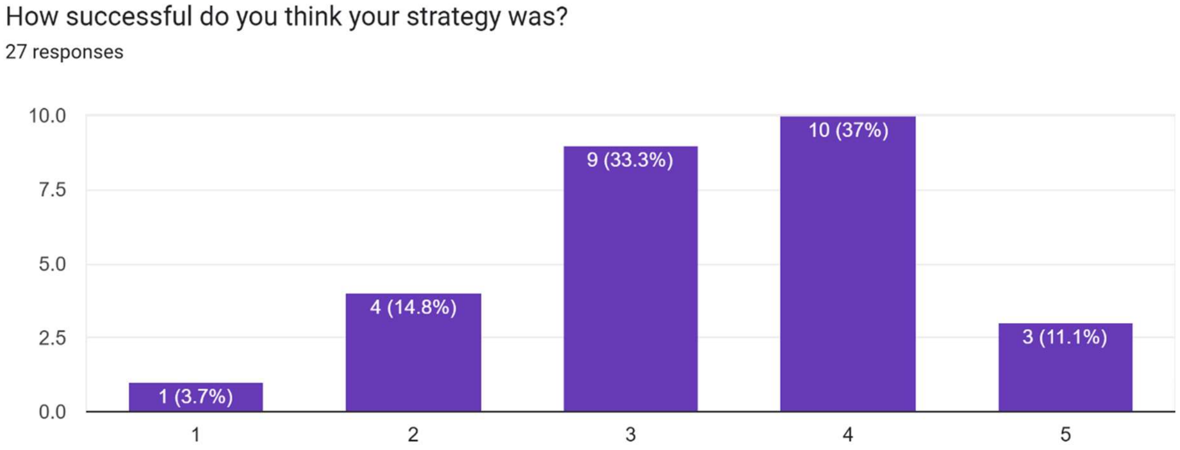

Figure 9 Strategies' Success Evaluation (own work)

The answers to the question on what the participants think is the major challenge in the fuel transition in the maritime industry can be allocated into four categories, Cost, Availability, Balance, Coordination.

Cost:

- "Cost"
- "Price"

Availability:

- "Availability" (x2)
- "Technical feasibility/scalability of alternative fuels"

- “Fuel availability”
- “The element of time and development of available technology”
- “The infrastructure on ships and in ports, and the choices within”
- “Time to achieve the goals”
- “Usability of fuels”

Balance/Alignment:

- “Being able to move as much cargo while remaining cost effective”
- “How to balance the money, and meet the requirements for shipping and CO_2”
- “Maintaining the budget and increasing productivity, while lowering CO_2 emissions”
- “Find the correct fuel, that would help reach the climate goals and also would keep all system competitive and sustainable”
- “Chicken egg discussion”
- “Supply and demand alignment”
- “Aligning costs with green benefits”
- “Safety, culture (habit) and economic factors of the new fuels and new technologies”
- “Cutting emissions while maintaining cargo capacity”
- “Reducing CO_2”

Coordination:

- “Coordination”
- “For the shippers its hard to buy new ships or buy waps, because the port stakeholders were the 1st one to buy there sources”
- “Alignment between shipping and the port”
- “The reciprocal pace of the fuel transition between ports and shipping firms”
- “Working together”
- “Stakeholder management”
- “Afstemming” [Coordination]
- “Ensuring that there is enough storage and bunkering facilities for the amount of shipping needed”
- “Communication”
- “Setting up the right strategy”

We can see, however, that the challenges mentioned the most are creating a balance between different aspects of the fuel transition, and the coordination of different stakeholders involved in the decarbonization of the maritime industry.

The following subchapters focus on the results of the port-led and shipowner-led transition test sessions. Participant responses are visualized in diagrams designed to trace their decision-making processes. Responses are also categorized by stakeholder groups, enabling identification of differences in strategies and reasoning.

4.2.2. Port-led Transition Scenarios

This section details the outcomes derived from the serious game, focusing on decision-making pathways, stakeholder interactions, and strategy evaluations within both port-led and shipowner-led transition scenarios. The analysis traces participant strategies from their initial formulation through subsequent revisions prompted by stakeholder dialogue, underscoring insights and appraisals of strategic efficacy. Each scenario is substantiated by detailed visual and tabular depictions of participant answers.

The port-led transition scenarios commence with Figure 10, which maps the decision-making trajectory from the shipping actors' perspective, illustrating the progression from initial strategies through discussion reflections to adapted approaches and final evaluations. Corresponding elaboration is provided in Table 3, detailing the interplay between stakeholder discussions and the perceived success of strategies on the shipping side. From the port viewpoint, Figure 11 presents an analogous decision flow, complemented by Table 4, which correlates discussion content with strategy outcomes among port participants.

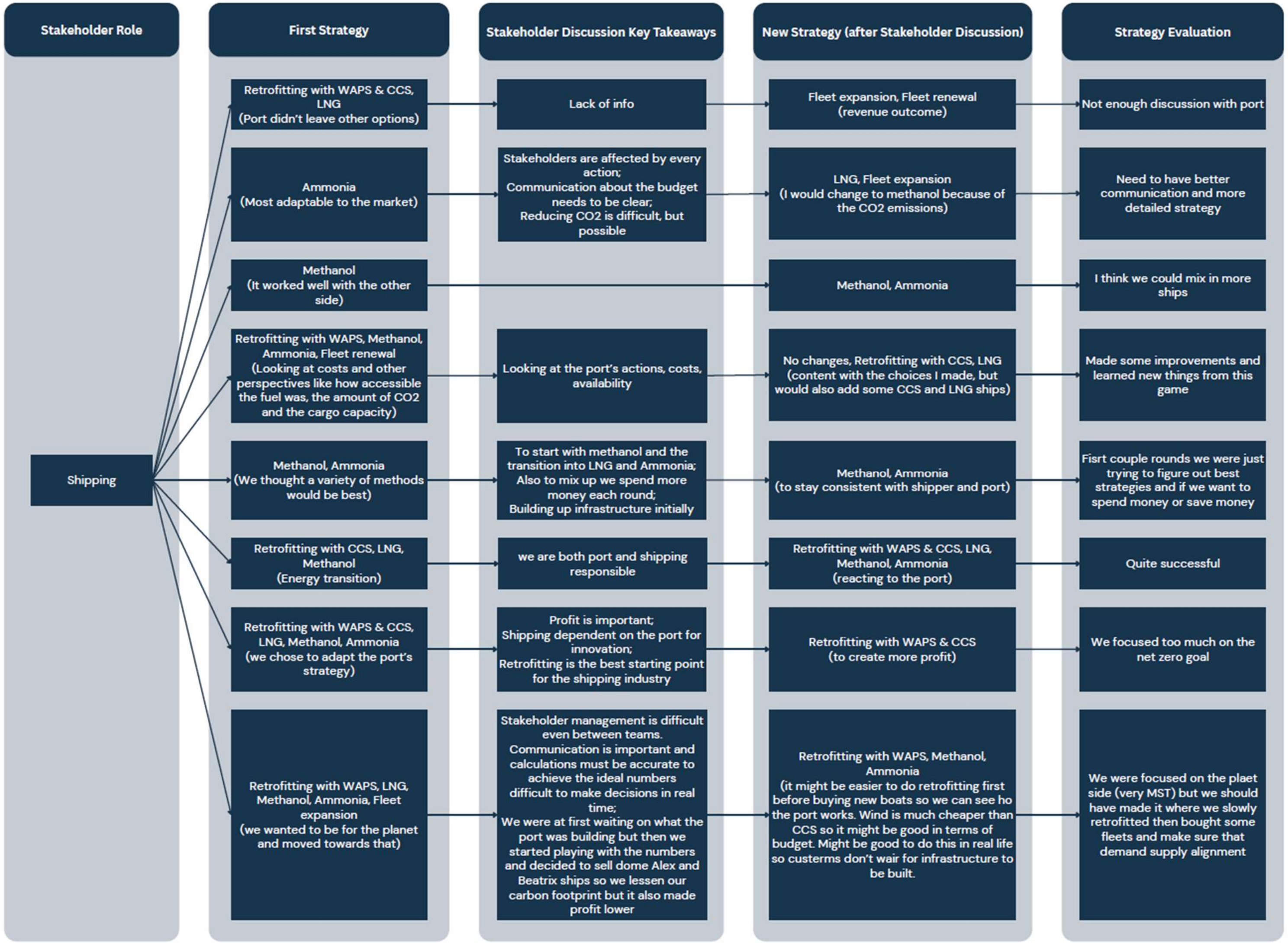

Figure 10 Decision-making process (Port-led transition, Shipping perspective) (own work)

No. Stakeholder Discussions	Key Takeaways of Stakeholder Discussions	Success (1 – 5)	Why
1	"Lack of info"	1	"Not enough discussion with port"
1	"- stakeholders are affected by every action." "- communication about budget needs to be clear." "- reducing CO_2 is difficult, but possible"	2	"Need to have better communication and a more detailed strategy"
2		4	"I think we could mix in more ships"
2	"Looking at the ports actions, costs, availability"	4	"Made some improvements and learnt new things from this game"
2	"To start with methanol and then transition into LNG and Ammonia. Also to mix up we spends more money each round. Building infrastructure up initially."	5	"First couple rounds we were just trying to figure out best strategies and if we want to spend more or save money"
1	"We are both port and shipping responsible"	4	"Quite successful"
2	"Profit is important. Shipping dependent on the port for innovation. Retrofitting is the best starting point for the shipping industry"	3	"We focused too much on the net zero goal"
2	"1. Stakeholder management is difficult even between teams. Communication is important and calculations must be accurate to achieve the ideal numbers 2. difficult to make decisions in real time 3. We were at first waiting on what the port was building but then we started playing with the numbers and decided to sell some Alex and Beatrix ships so we lessen our carbon footprint but it also made the profit lower"	3	"We were focused on the planet side (very MST) but we should have made it where we slowly retrofitted then bought some fleets and make sure that demand supply alignment"

Table 3 Relation between Stakeholder Discussions & Strategies' success (Port-led transition, Shipping perspective) (self-compiled)

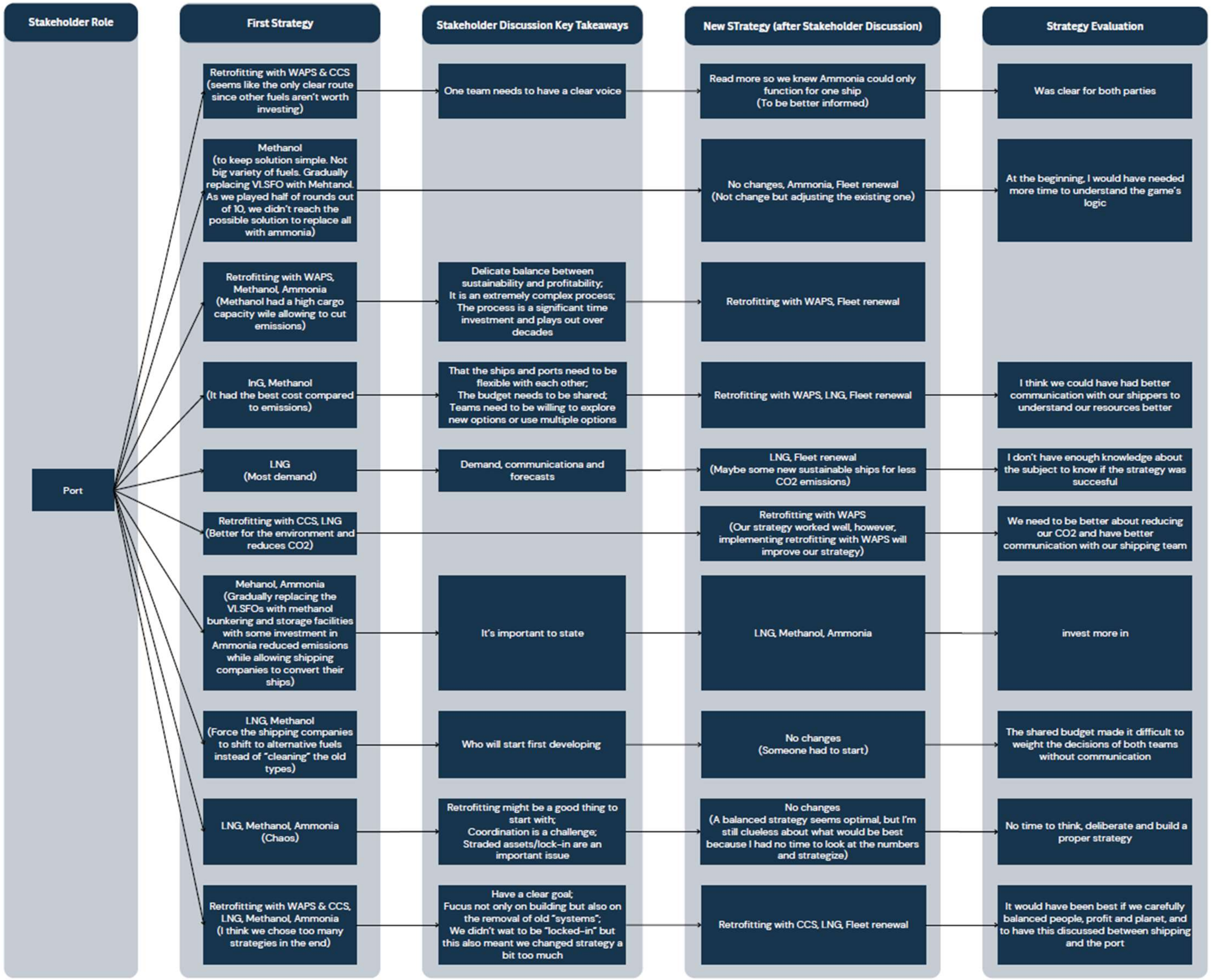

Figure 11 Decision-making process (Port-led transition, Port perspective) (own work)

No. Stakeholder Discussions	Key Takeaways of Stakeholder Discussions	Success (1 – 5)	Why
1	"One team needs to have a clear voice"	5	"Was clear for both parties"
2		3	"At the beginning, I would have needed more time to understand the game's logic"
2	"- Delicate balance between sustainability and profitability - It is an extremely complex process - the process is a significant time investment and plays out over decades"	5	
2	"That the ships and ports need to be flexible with each other, the budgets need to be shared, teams need to be willing to explore new options or use multiple options"	3	"I think we could have had better communication with our shippers to understand our resources better"
2	"Demand, communication and forecadts"	3	"I don't have enough knowledge about the subject to know if the strategy was successful"
2		3	"We need to be better about reducing our CO_2 and have better communication with our shipping team"
2	"It's important to state"	4	"Invest more in"
1	"Who will start first developing"	4	"The share budget made it difficult to wight the decisions of both teams without communication"
2	"Retrofitting might be a good thing to start with; Coordination is a challenge; Stranded assets/lock-in are an important issue"	2	"No time to think, deliberate and build a proper strategy"
2	"1. Have a clear goal 2. Focus not only on building but also on the removal of old "systems" 3. We didn't want to be in "lock-in" but this also meant we changed strategy maybe a bit too much."	2	"It would have been best if we carefully balanced people, profit and planet > and to have this discussed between shipping and the Port"

Table 4 Relation between Stakeholder Discussions & Strategies' success (Port-led transition, Port perspective) (self-compiled)

4.2.3. Shipowner-led Transition Scenarios

The shipowner-led transition scenarios are addressed starting with Figure 12, which portrays the evolution of decision-making among shipping stakeholders, capturing strategic shifts alongside dialogue outcomes and success ratings. These findings are synthesized in Table 5, documenting the influence of stakeholder interactions on shipowners' strategy effectiveness. From the port perspective, Figure 13 visualizes the decision-making pathway, while Table 6 links discussion elements to the perceived success of port stakeholder strategies.

Collectively, these figures and tables enable a comprehensive understanding of how the choice of leadership in fuel transition decisions, whether port- or shipowner-led, shapes coordination dynamics, strategy recalibrations, and perceived success of decarbonization efforts within the simulated environment.

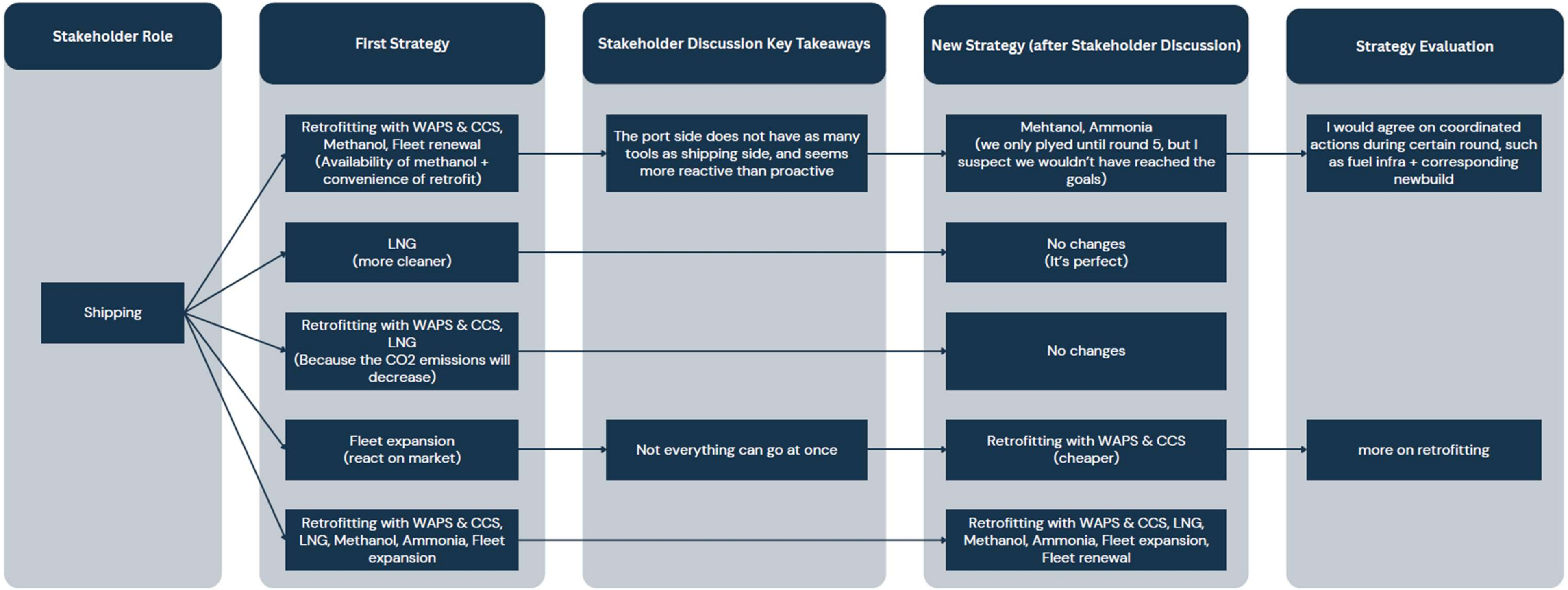

Figure 12 Decision-making process (Shipowner-led transition, Shipping perspective) (own work)

No. Stakeholder Discussions	Key Takeaways of Stakeholder Discussions	Success (1 – 5)	Why
2	"The port side does not have as many tools as shipping side, and seems more reactive than proactive"	4	"I would agree on coordinated actions during certain rounds, such as fuel infra + corresponding new-build"
1		4	
1	"No"	3	
1	"not everything can go at once."	2	"more on retrofitting"
2		2	

Table 5 Relation between Stakeholder Discussions & Strategies' success (Shipowner-led transition, Shipping perspective) (self-compiled)

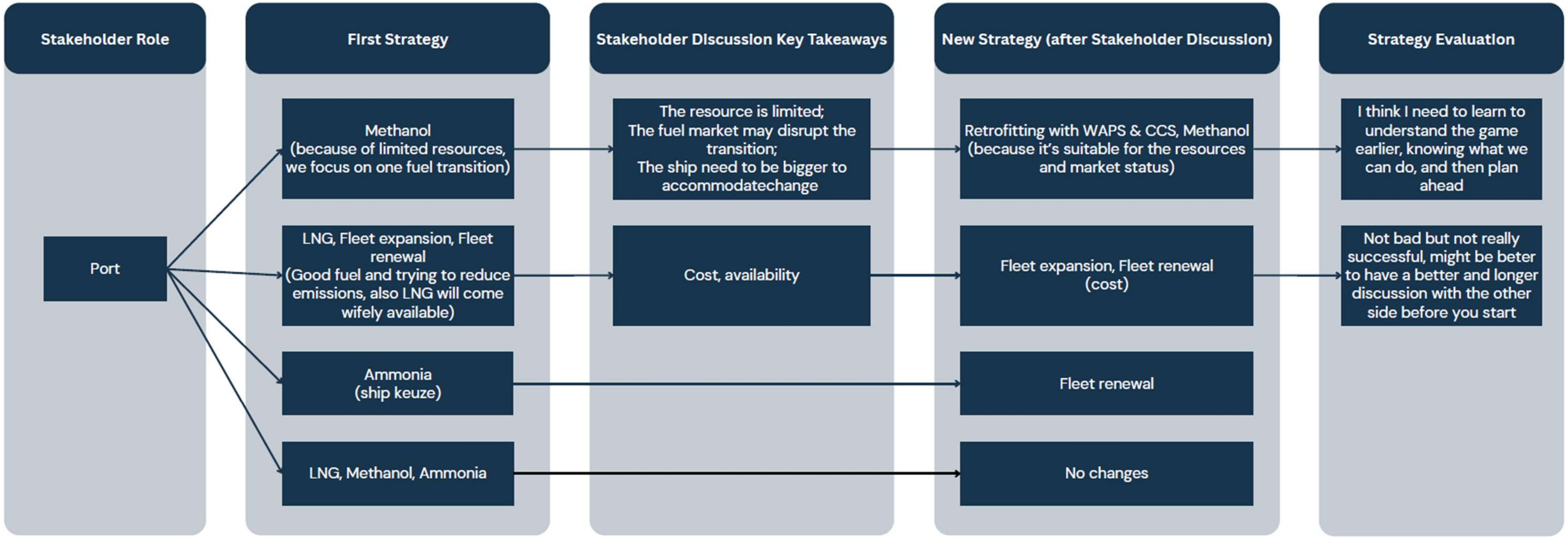

Figure 13 Decision-making process (Shipowner-led transition, Port perspective) (own work)

No. Stakeholder Discussions	Key Takeaways of Stakeholder Discussions	Success (1 – 5)	Why
1	"First time we did not yet have overview of the situation"	4	"Miscalculations"
2	"1. The resource is limited 2. The fuel market may disrupt the transition 3. The ship need to be bigger to accommodate the change"	4	"I think I need to learn to understand the game earlier, knowing what we can do, and then plan ahead"
2	"Cost, availability"	3	"Not bad but not really successful, might be better to have a better and longer discussion with the other side before you start"
1			
1		4	

Table 6 Relation between Stakeholder Discussions & Strategies' success (Shipowner-led transition, Port perspective) (self-compiled)

4.2.4. Scenario Analysis

Analysis of Tables 3 through 6 (sub-chapters 4.2.2 and 4.2.3) suggests that more frequent stakeholder discussions correlate with strategy success. The following key challenges appear repeatedly:

- Insufficient communication
- Insufficient coordination
- Lack of information/knowledge
- Difficulty of aligning different strategies of different stakeholders
- Difficult resource management

The analysis of stakeholder discussions highlights key dynamics shaping maritime decarbonization, revealing a complex interdependence among communication, coordination, information sharing, learning, alignment, and resource management. A clear and unified voice within teams, coupled with transparent communication about budgets and environmental goals, emerged as essential. Stakeholders feel deeply impacted by each decision, emphasizing that effective management depends on ongoing, robust communication. Yet challenges persist. Port-side actors are often seen as reactive rather than proactive, limited by a small set of tools, which hinders forward-looking strategic engagement. Participants regularly pointed to strategic gaps, including insufficient cross-stakeholder dialogue, and poor communication of resources. Success appeared linked to dedicating more time to joint discussions that foster a shared understanding of strategic options.

Coordination remains a major challenge with participants highlighting risks such as stranded assets and technological lock-in as significant barriers. The uncertainty over who should lead development efforts was clear, prompting calls for greater team flexibility, diverse exploration of solutions, and fair sharing of responsibilities between ports and shipowners. Managing stakeholders grew more complex due to the need for precise communication and coordination mechanisms. Strategy evaluations highlighted the advantages of synchronized actions within defined rounds, particularly aligning fuel infrastructure investments with new vessel orders, but also showed that shared budgets complicate joint decision-making without strong communication frameworks. Participants stressed the importance of improved planning and continuous strategic dialogue to balance People, Profit, and Planet objectives. Some cautioned that exclusive focus on net-zero targets risks weakening overall strategy, advocating instead for a balanced, phased approach, such as staged retrofitting and gradual fleet expansion, to better align supply and demand.

Stakeholders initially faced significant challenges due to limited data and low situational awareness, particularly concerning port activities, associated costs, and fuel availability. Uncertainties about demand projections and the need for accurate forecasting were repeatedly emphasized as critical areas for improvement. Participants outlined strategic pathways involving an initial shift to LNG followed by a transition to ammonia, dependent on gradual infrastructure development, plans that require transparent and timely information sharing. Evaluations showed that many participants needed extended time to grasp the game's complexity and range of options. Early rounds were dominated by balancing immediate expenditures against financial caution. Despite these initial struggles, iterative learning became evident as later rounds reflect deeper understanding and more sophisticated decision-making.

Learning reflections revealed a widespread understanding that effective maritime decarbonization is a long-term, resource-intensive endeavor, with retrofitting recognized as a vital early strategy. Participants acknowledged persistent coordination challenges, and the risks associated with technological lock-in, highlighting the importance of adapting strategies to avoid such pitfalls as a major takeaway. While the sessions were praised for improving conceptual understanding and strategic flexibility, limited time for reflection sometimes constrained the development of fully thought-through approaches.

Discussions on alignment emphasized the need for leadership by a single team and shared openness to a wide range of solutions, including both the implementation of new systems and the decommissioning of old ones. A foundation of shared responsibility between ports and shipowners was seen as crucial, with clear communication and exact calculation essential to achieving the best outcomes. Strategy reviews identified successful examples of alignment, particularly where fuel infrastructure development was closely coordinated with vessel acquisitions. However, participants called for longer, more in-depth cross-stakeholder engagement to strengthen results, underscoring the importance of balancing social, economic, and environmental objectives in an integrated manner. Phased retrofitting and carefully managed fleet expansion were highlighted as practical approaches to address supply-demand challenges.

Resource-related insights highlighted the significant impact of limited capital, fuel costs, and availability on decision-making pathways. Fuel market volatility adds risks to the transition, while larger vessel sizes may be required to accommodate new technologies and alternative fuels. Although retrofitting is financially demanding, it remains a practical entry point, with infrastructure investments similarly constrained by budget realities. Participants recognized the crucial dependence of shipowners on ports for innovation and progress, emphasizing the need for clear communication to align resource allocation. However, shared budgets complicated resource optimization and occasionally led to suboptimal outcomes. Experiments with investment timing showed a preference for gradual, phased approaches, starting with retrofitting and followed by fleet renewal, which helped better match capacity and demand.

In summary, the integrated findings from stakeholder discussions and strategy evaluations reveal the complex and interconnected challenges of maritime decarbonization. Persistent gaps in communication and alignment between ports and shipowners emerged as key obstacles to effective decision-making. Coordination was complicated by budget constraints, unclear roles, and the need for phased implementation, all of which slowed progress. Early information shortages hindered strategic development, but adaptive learning fostered iterative improvement over time. Resource limitations, financial, technological, and infrastructural barriers, continue to pose significant challenges, highlighting the importance of clear, shared planning and shared responsibility. Ultimately, the findings emphasize that balancing People, Profit, and Planet requires gradual, well-coordinated action rooted in transparent dialogue and flexible, phased strategies.

4.3. Comparative Analysis of Transition Strategies

The following graphs compare strategic choices made by participants presenting the port and shipping stakeholders within port-led and shipowner-led transition scenarios. The graphs display the frequency of each strategy choice, distinguishing between port-led and shipowner-led contexts. However, they do not display the combinations of these strategy choices. Figures 14 and 15 present the initial strategies selected before stakeholder discussions, whereas Figures 16 and 17 illustrate the strategies adopted after these discussions. These figures capture how often each stakeholder group chose specific strategy keywords, highlighting shifts in priorities resulting from the collaborative dialogue.

The stakeholder discussions notably influenced strategic priorities, with increased emphasis on areas such as fleet renewal and retrofitting, reflecting the evolving nature of decision-making throughout the transition process. While the diagrams offer a quantitative summary of strategy frequencies, qualitative insights into stakeholder collaboration and the effectiveness of adopted strategies further illuminate the dynamics behind these shifts.

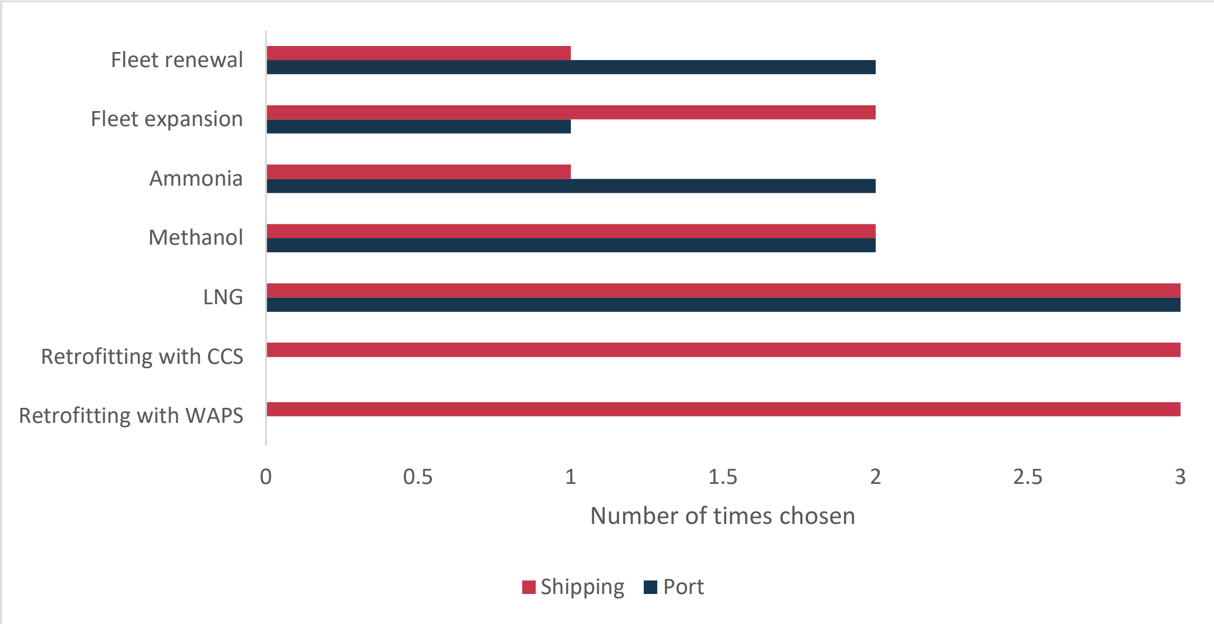

Figure 14 1st Shipowner-led transition strategies (own work)

Figure 15 1st Port-led transition strategies (own work)

Figure 16 Adapted Shipowner-led transition strategies (own work)

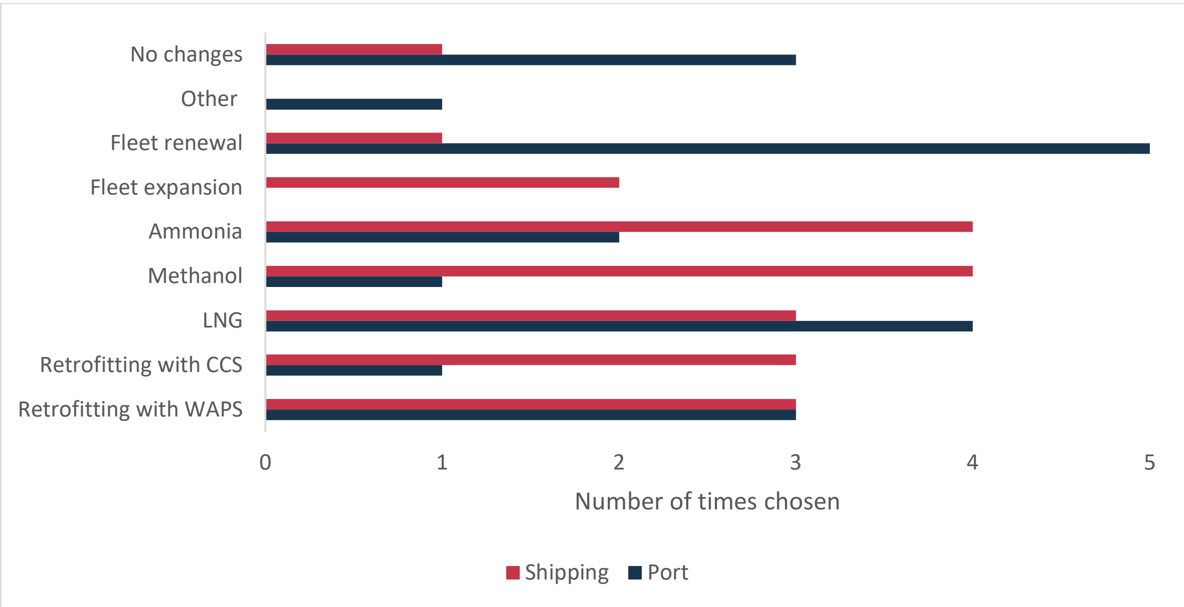

Figure 17 Adapted Port-led transition strategies (own work)

Overall, the shipowner group exhibited a more diverse strategic approach across all scenarios, possibly due to the port's lack of involvement in vessel retrofitting. LNG emerged as the most frequently chosen strategy component, with Methanol and Ammonia preferred particularly by shipowners. Moreover, fleet renewal and expansion are featured more prominently in ship-owner-led scenarios.

4.4. Interview Insights

The interviews with stakeholders from the maritime industry offered diverse but complementary perspectives on the challenges and enablers of the maritime fuel transition. In the following, each interview is summarized.

4.4.1. Port Experts

The interview with Francesca Morucci, senior representative in the Transparency, anti-corruption, training, and promotion department of Autorità di Sistema Portuale del Mar Tirreno Settentrionale (the North Tyrrhenian Port Network Authority), provided valuable real-world validation of several patterns observed during testing sessions of the mission “Future Fuels”. As a key stakeholder actively engaged in port-city issues, among which decarbonization efforts across multiple Italian ports belonging to the Tyrrhenian network, Morucci offered a nuanced perspective on both the operational and institutional complexities inherent to the fuel transition. A prominent parallel between the game outcomes and the interview was the critical importance of stakeholder collaboration. Game participants frequently reported increased confidence in their strategies when they afforded opportunities for cross-team dialogue. Morucci emphasized this dynamic by showcasing the “Blue Agreement” in Livorno, which united the port authority, shipping companies, the harbor master, and municipal officials. While acknowledging the persistent challenge of converting dialogue into concrete action, Morucci underscored the necessity of structured, sustained engagement among stakeholders.

The interview also affirmed the game’s simulation of dynamic decision-making. Players tended to start with one fuel strategy but often pivoted toward alternatives in response to evolving constraints. Morucci confirmed that similar adjustments occur in practice, as technological uncertainties, regulatory pressures, and shifting resource availability compel ports and companies to revise their plans midstream. For example, significant investments in onshore power supply (OPS) have recently been tempered by concerns over national energy capacity, calling into question OPS’s long-term viability as a singular decarbonization solution.

Financing emerged as a central theme, resonating strongly both in gameplay and professional contexts. Morucci estimated that financing availability, from EU funds, national governments, of internal resources, accounts for over 80 % of the feasibility of implementation. She emphasized that, regardless of collective will or technical readiness, progress is severely constrained without adequate financial support.

Regarding leadership of the transition, the interview highlighted a more fluid reality than the game’s turn-based structure suggests. Morucci observed that while ports initially drove change,

often in response to public and environmental pressures, some shipowners have recently taken proactive initiatives, prompting ports to adapt in turn. In her view, the focus should shift from prioritizing sequential actions to enhancing the readiness and adaptability of all involved stakeholders.
Finally, Morucci reflected on the potential role of serious games in professional settings. She recognized their value in fostering the exploration of diverse perspectives and stimulating discussion but cautioned that not all stakeholders may be ready to adopt such methods, especially within formal or hierarchical organizational contexts. Nevertheless, she acknowledged the suitability of serious games for educational environments, industry workshops, and cross-sectoral meetings, particularly when facilitated by neutral third parties.

The interview with Pratham Solanki, a consultant specializing in Port Finance and Strategy at MTBS, provided critical reinforcement and occasionally a constructive counterpoint to behavioral patterns observed during the testing sessions. His insights grounded the discussion in the practical realities of capital investment, governance structures, and policy enforcement.
A central theme emphasized by Solanki was the decisive role of capital expenditure (CAPEX). He noted that while technical feasibility rarely limits implementations such as OPS, the fundamental barrier lies in the return on investment. Without substantial public funding, subsidies, or concessional financing, private stakeholders often find it difficult to justify these capital-intensive investments. This observation closely aligns with simulation behavior, where participants exhibited hesitation to commit resources to heavy infrastructure unless appropriate incentives or cost-sharing mechanisms were present.
Solanki challenged the simulation's implicit duality between port-led and shipowner-led transitions. Drawing from his experience, he argued that transformative change is predominantly policy-led, driven by government mandates or international agreements. For illustration, he referenced the India-Netherlands green corridor memorandum of understanding (MOU), where regulatory direction prompted port investments, and shipowners adjusted to the resulting infrastructure landscape.
The familiar chicken-and-egg dilemma resurfaced in the context of governance. Solanki highlighted that responsibility is not simply divided between ports and shipowners but is fundamentally shaped by regulatory frameworks. He mentioned instances where OPS infrastructure remained underutilized due to the absence of mandated usage, demonstrating that without legal enforcement, infrastructure investments may fail to yield environmental benefits.

Regarding stakeholder communication, Solanki adopted a pragmatic stance. While acknowledging the value of dialogue, he contended that enforceable regulations are indispensable. Effective decarbonization, in his view, hinges less on consensus-building and more on compliance with binding environmental standards. This perspective contrasts with the testing session findings where cross-team discussions correlated with improved strategy confidence, underscoring the reality that dialogue alone must be supported by robust regulatory mandates.

Finally, Solanki emphasized the necessity of adopting a supply-chain-wide perspective. He stressed that the fuel transition extends beyond port-shipowner interactions to encompass upstream production capacity, logistics frameworks, and global trade dynamics. For example, nations generating ammonia or hydrogen at scale require corresponding export infrastructure and logistical readiness. He noted that such complexities are simplified in the current game design, which omits upstream supply constraints. Consequently, Solanki suggested incorporating macroeconomic indicators and geopolitical variables in future game iterations to more accurately reflect the multifaceted nature of maritime fuel transition.

4.4.2. Shipping Experts

The interview with Jeroen Pruyn, an academic expert actively involved in maritime energy transition projects, provided valuable confirmation and elaboration of the dynamics observed during the PortConstructor testing session. His insights grounded the theoretical framework of the serious game within the practical complexities of multi-stakeholder maritime decarbonization.

A recurrent theme linking both the game and the interview was the pivotal role of knowledge exchange. During testing, participants who engaged more frequently in stakeholder discussions exhibited greater confidence in their strategies. Pruyn reinforced this by emphasizing that structured discussions are not merely beneficial but essential. He described these dialogues as a "learning mechanism" that enables stakeholders to surface and challenge assumptions, understand interdependencies, and reassess entrenched viewpoints. For example, he recounted how knowledge gaps between fuel suppliers, shipowners, and financiers were effectively bridged when all the parties convened in a national roadmap initiative.

Pruyn also highlighted structural barriers affecting cooperation, noting that stakeholder configurations significantly influence project feasibility. Ports with centralized infrastructure ownership, such as power or sewage systems controlled by a single authority, face coordination challenges distinct from those in jurisdictions characterized by fragmented governance and dispersed responsibilities. This heterogeneity imposes logistical difficulties and complicates the alignment of financial, regulatory, and operational objectives across entities.

Fuel choice, a major element of the game, was discussed extensively. While the game simplified fuel options to LNG, methanol, and ammonia, Pruyn observed that methanol currently enjoys preference among shipowners owing to its low entry barriers and operational flexibility. This preference, he noted, stems less from sustainability or efficiency considerations and more from industry risk aversion amid regulatory uncertainty and fuel availability concerns. Meanwhile, ammonia, despite its theoretical promise, confronts challenges related to toxicity, limited engine readiness, and public acceptance.

On leadership in decision-making, Pruyn underscored the decentralized nature of the decarbonization transition. Ports do not necessarily dictate future fuel adoption but influence outcomes by deciding which fuels to accommodate, thus shaping the operational environment for shipowners. Nonetheless, many critical variables, such as fuel cost competitiveness and scalability, remain beyond the direct control of both ports and shipowners, being driven largely by broader geopolitical factors and energy market dynamics.

Financial viability emerged as a further constraint. Cost pressures and volatile fuel prices have delayed progress even on well-funded pilot projects. Pruyn illustrated this with the stagnation of hydrogen vessel initiatives amid soaring energy prices, contrasting with the relatively smoother advancement of LNG and methanol projects. This observation reflects game behavior, where players frequently prioritized retrofitting and operational efficiency before committing to alternative fuels.

Finally, Pruyn reflected on the role of simulation tools and serious games like PortConstructor, characterizing serious games as “safe spaces” that allow decision-makers to explore unfamiliar scenarios and experiment with strategies that may be too risky in real life. He emphasized their value in early-stage collaboration, fostering trust and knowledge exchange among stakeholders. At the same time, he cautioned that such tools should be positioned as exploratory environments rather than definitive predictive models, serving to test assumptions and stimulate constructive dialogue.

Insights from the interview with Annet Koster, Managing Director, and Nathan Habers, Director Communications and External Affairs, of the Royal Association of Netherlands Shipowners (KVNR) offered a nuanced and at times critical perspective on the decision-making and cooperation dynamics central to maritime decarbonization. Contrasting with more optimistic views

of collaboration, the discussion highlighted the persistent tensions between ambition and feasibility, notably regarding financial risk, technological uncertainty, and stakeholder alignment.
When asked to identify the primary enablers and barriers to cooperation in decarbonization efforts, the participants consistently highlighted fuel availability, lack of supporting infrastructure and the cost differential between conventional and alternative fuels. These three factors were repeatedly characterized as critical thresholds in decision making processes within companies. Without their resolution, subsequent progress is unlikely. Beyond these, Koster and Habers emphasized the broader systemic challenge in the maritime sector, often descried as an "ecosystem problem". They noted that the sector is rarely treated as a fully integrated chain. Instead, stakeholders typically hold only partial views with limited visibility or incentives to address the collective challenges. A particularly illustrative example concerned financial institutions, which face a paradox: while advocating for greener investments, they remain hesitant to finance vessels powered by underdeveloped fuel technologies.
This fragmentation contributes to what was described as a classic chicken-and-egg dilemma: lack of demand inhibits production; absence of production constrains infrastructure; and insufficient infrastructure hinders demand. At the core of this cycle lies the need for certainty, not solely regarding fuel technologies, but also encompassing long-term contracts, charterer commitments, and port infrastructure readiness. It was remarked that in many cases, the issue is not purely financial but fundamentally about assurance that an investment will yield returns over its lifespan.
Whereas the previous interview underscored the positive impact of multi-stakeholder discussions, Koster and Habers adopted a more circumspect stance. They acknowledged the value of dialogue but stressed that discussions must result in actionable business cases to effect change. As one participant put it, "You can bring them together as often as you want, but if you can't finalize the business case, nothing moves." This perspective aligns with observations from the testing session, where players correlated increased interaction with greater strategic confidence, while limited engagement fueled frustration. Notably, both in the game and real-world dynamics, alignment tended to arise less from formal rules and more from iterative exposure, negotiation, and adaptive strategy evolution.
Regulatory "sticks" emerged as a further critical theme. The interviewees emphasized that shipowners alone cannot drive the full transition to low-carbon fuels. Regional and global regulatory frameworks, such as FuelEU Maritime, the EU ETS, and upcoming IMO measures, were cited as essential to creating a level playing field. However, they also cautioned against regulatory fragmentation across jurisdictions, which risks inefficiencies and may divert investment

away from substantive innovation. Ideally, regulatory revenues would be recycled into fuel production, infrastructure upgrades, and vessel retrofitting initiatives.
On the topic of retrofits, the participants confirmed a prominent trend reflected in the simulation: shipowners tend to favor retrofitting solutions before transitioning fully to alternative fuels. Two coexisting pathways were identified: investment in newbuilds equipped with flexible propulsion systems (e.g., diesel-electric) and retrofitting existing fleets with energy-saving technologies such as WAPS or anti-fouling coatings. Although these remain indispensable well into 2050, given the current high costs and uncertainties surrounding alternative fuels.
Trust and collaboration within the ship owning community also featured prominently. While collaboration is feasible, it usually depends on clear business incentives and pre-existing relationships grounded in trust, frequently underpinned by long-term personal or financial ties. Competitive market dynamics can impede cooperation. Nonetheless, examples exist of shipowners exploring joint newbuilding programs or coordinated strategies, especially when constrained by common infrastructure or fuel supply challenges.

4.5. Integration of Game Results and Industry Perspectives

The integration of the Port Constructor "Future Fuels" testing results with the perspectives gathered in the four interviews reveals strong alignments on several structural dynamics in maritime decarbonization, while also exposing differences driven by the constraints and realities of professional practice.
A key alignment emerging from both the game testing sessions and expert interviews was the positive correlation between frequent stakeholder interaction and reported strategic confidence. Whitin the game, sessions featuring more frequent cross-team exchanges between ports and shipowners consistently yielded higher self-assessed strategy success and more coherent investment trajectories. Pruyn characterized this phenomenon as a "learning mechanism", facilitating the surfacing of assumptions and the alignment of diverse perspectives. Likewise, Morucci referenced the "Blue Agreement" in Livorno as a real-world instance where sustained, structured dialogue convened varied actors, fostering enhanced mutual understanding.
Nevertheless, findings from both the game and interviews underscored that dialogue alone is insufficient. Koster and Habers emphasized that discussions must lead to actionable business cases to sustain momentum. Without this momentum, progress quickly stalls. This dynamic was also evident in the testing sessions, where teams experienced high interaction but lacked coordinated investment strategies, resulting in underperformance. Solanki further reinforced this

view by stressing the necessity of enforceable regulatory frameworks, highlighting that discussions must be coupled with binding commitments to realize tangible outcomes.

The recurring “chicken-and-egg” dilemma, whether ports or shipowners should initiate decarbonization efforts, manifested prominently across both domains. In the game, participants frequently hesitated to commit to alternative fuel infrastructure without clear uptake, while shipowners deferred vessel retrofits pending infrastructure certainty. Interviewees elaborated on this cycle from complementary perspectives. Koster and Habers framed it as a systemic ecosystem challenge, necessitating concurrent advancement in supply chains, market demand, and infrastructure provision. Solanki introduced a governance dimension, noting that infrastructure investments can remain idle without mandated utilization policies. Together, these insights emphasize that resolving this obstacle requires coordinated action by all stakeholders, supported by regulatory measures ensuring timely investment and effective deployment.

Furthermore, both game participants and interviewees preferred incremental, phased strategies over one-off, irreversible commitments. Game players tended to initiate transitions via operational efficiency enhancements and retrofitting before embracing alternative fuels, paralleling Pruyn’s observation that industry actors favor low-risk, reversible interventions initially. Koster and Habers, and Morucci confirm the sustained importance of retrofits, describing some shipowners’ parallel strategies of retrofitting existing fleets alongside commissioning newbuilds equipped with flexible propulsion systems. This staged approach reflects both financial constraints and ongoing uncertainty concerning which fuels will achieve long-term viability.

Budgetary constraints within the game often compelled participants to forgo ideal strategies in favor of alternatives offering quicker returns or requiring lower capital outlay. The interviews not only affirmed this behavior but elaborated with greater nuance. Morucci estimated that funding availability accounts for over 80 % of a project’s viability, while Solanki identified CAPEX as the predominant determinant in port infrastructure initiatives. Both Pruyn, and Koster and Habers highlighted that financial uncertainty, not merely funding scarcity, can be equally immobilizing, as stakeholders are reluctant to commit without predictable costs and secure contractual frameworks.

While the game integrates regulatory frameworks as a background parameter, its direct influence on participant decision-making appeared less pronounced than emphasized in the interviews. Interviewees consistently portrayed regulation as a primary catalyst for action. Solanki highlighted that ports and shipowners frequently respond to mandatory policy requirements rather than voluntary collaboration. Koster and Habers stressed the critical need to harmonize

international regulations to prevent market distortions, whereas Pruyn and Morucci pointed to the risks posed by fragmented regulatory regimes undermining effective investment planning.
These insights suggest that although the game effectively simulates stakeholder negotiation and resource allocation processes, it underrepresents the catalytic and directive role of policy instruments in shaping strategies.

Within the game, participants occasionally prioritized environmental outcomes over profitability, experimenting with strategies characterized by high costs and low financial returns. In contrast, industry representatives uniformly filtered their decisions through the lens of commercial viability. Koster's and Habers' position was notably pragmatic, emphasizing that sustainability measures must align with prevailing market realities, and that customer willingness to pay premiums for greener shipping remains limited.

Furthermore, the game's primary focus on interactions between ports and shipowners operates under simplified assumptions regarding fuel supply chains and upstream production. Interviews highlighted the limitations of this narrow scope, noting that the maritime fuel transition depends on the readiness of the entire supply chain, encompassing production capacity, logistic infrastructure, and geopolitical trade flows. Without incorporating these factors, the game risks oversimplifying the complex environment within which real-world decisions are made.

The integrated findings indicate that while PortConstructor game captures many essential decision-making dynamics, particularly the significance of communication, phased investment, and actor interdependence, its realism and applicability could be enhanced by incorporating:

1. Regulatory enforcement mechanisms and their decisive effects on strategy adoption.
2. Full supply chain interdependencies, spanning from fuel production through delivery.
3. Economic risk factors, including fuel price volatility and financing conditions.

Incorporating these elements would increase the game's fidelity to operational realities described by industry experts and strengthen its utility as a tool for stakeholder training, early project design, and multi-sectoral dialogue facilitation.

5. Conclusion

5.1. Key Findings and Concluding Answers to the Research Questions

The maritime industry's decarbonization presents multifaceted challenges, which can be categorized into regulatory complexities, technological uncertainties, operational and infrastructural challenges, financial and investment constraints, and human and cultural factors. This intricate landscape requires balancing environmental targets with operational and economic realities, such as investing in new technologies, managing fleet renewal, and adapting infrastructure for alternative fuels. Understanding how different actors (ports and shipowners) initiate and influence transition decisions is crucial, as their approaches impact the overall success of decarbonization efforts. Through simulation and expert validation, these challenges underscore the need for coordinated strategies that consider both technological advancements and the human factors driving maritime sustainability.

Success relies on enhancing communication channels, fostering adaptive learning, coordinating financing strategies, and aligning port and shipowner objectives. Serious games offer a powerful avenue to reveal and address these complexities, effectively mirroring the nuanced reality faced by industry actors.

The serious game testing sessions alongside expert interviews highlighted that maritime decarbonization as a complex, interdependent process in which ports and shipowners hold distinct but closely connected roles. Ports, responsible for providing bunkering services and developing green fuel infrastructure, struggle with long lead times, significant financing demands, and regulatory challenges that constrain their flexibility. In contrast, shipowners exercise greater strategic autonomy by managing fleet renewal, retrofitting, and diversifying fuel sources. The findings emphasize that collaboration is critical: effective communication, shared responsibilities, and aligned incentives consistently lead to better outcomes, while information gaps and disputes over budget allocation impede progress. Participants balanced ongoing tensions between emission reduction, cargo capacity maintenance, and profitability, weighing short-term retrofitting options, such as WAPS or CCS, against long-term fleet renewal, each presenting trade-offs in cost, capacity, and risk. LNG and methanol emerged as feasible near-term fuels, with growing consideration of ammonia for the future. However, uncertainties in fuel pricing, supply reliability, and regulatory frameworks underline the necessity for diversified, flexible strategies alongside phased infrastructure investments. Increasingly influential regulatory measures, including EEXI, CII, and the EU ETS, highlight the need for stable and predictable policy environments to enable timely, confident decision-making. The serious game proved instrumental in revealing underlying assumptions, highlighting stakeholder interdependencies, and fostering iterative, adaptive planning processes. Ultimately, successful maritime decarbonization depends on harmonizing stakeholder priorities, incrementally developing infrastructure, and employing decision-support tools that integrate environmental and economic objectives from the outset.

Sub-Research Question 1: What are the current maritime decarbonization challenges faced by ports and shipowners?

Ports face several significant challenges in advancing maritime decarbonization. Financial constraints limit the resources available for environmental investments and decarbonization training, constraining their capacity to act decisively. Simultaneously, ports must develop and expand alternative fuel bunkering infrastructure in an environment characterized by considerable uncertainties pertaining to fuel availability, cost, safety, and environmental compatibility. Navigating a patchwork of regulatory frameworks across diverse jurisdictions further complicates their efforts, requiring adaptability and strategic alignment with varying policy contexts. Additionally, ports struggle with managing multiple institutional roles and responsibilities while fostering the necessary organizational change to support a decarbonized future. Central to these difficulties is the complex task of coordinating infrastructure investments effectively to meet the evolving needs of shipowners.

Shipowners, on their part, confront substantial barriers as well. The high capital expenditures and financial uncertainties associated with adopting emerging alternative fuel technologies pose significant hurdles. Many operate legacy fleets comprised of older, less energy-efficient vessels, which limits opportunities for retrofitting and complicates timely fleet renewal. Moreover, access to sufficient information and technical knowledge remains insufficient, particularly among smaller operators who may lack the capacity to navigate these complex transitions. Market risks stemming from volatile fuel prices and inconsistent availability of supporting infrastructure exacerbate these challenges. Contractual and procurement complexities further constrain shipowners, although policy-driven market-pull mechanisms can provide important incentives and support. There is also an inherent risk of technological lock-in and stranded assets if transitions are not strategically planned and carefully managed to accommodate evolving technologies and market conditions.

Both ports and shipowners share overarching challenges related to coordination and communication. The difficulty of aligning diverse stakeholder objectives and actions frequently hampers progress. Additionally, both parties must continually balance the imperative of reducing environmental impact with the practical demands of maintaining profitability and operational feasibility. This delicate balance remains one of the most persistent and complex issues in the maritime decarbonization process.

Sub-Research Question 2: What are key factors influencing the effectiveness of port-led vs. shipowner-led approaches in selecting and implementing alternative fuel strategies?

Effective coordination in the maritime decarbonization process hinges on transparent and ongoing information and knowledge exchange. This encompasses communication about budgets, fuel availability, costs, and environmental impacts. Although ports typically possess fewer decision-making tools and more limited capacity compared to shipowners, they fulfill a critical enabling role by providing the necessary infrastructure. Conversely, shipowners require clear, reliable information to inform their planning of vessel retrofits and newbuilds, underscoring the interdependency of their decisions.

Financial viability and risk management loom large as central concerns. Shipowners focus intensely on profitability and the availability of capital, which often constrains their capacity to invest in greener technologies. Ports face their own challenges in managing infrastructure investments that carry uncertain returns, frequently necessitating subsidies or supportive regulatory frameworks to justify expenditure and reduce financial risk.

Strategically, timing and adaptation are fundamental. Port-led approaches generally prioritize phased, infrastructure-first strategies that lay the groundwork for transition. Shipowners, in turn, emphasize retrofitting existing fleets and pursuing fleet renewal, often responding reactively to the infrastructure provided by ports. Greater synchronization and mutual adaptation between these stakeholders consistently yield improved outcomes, highlighting the importance of coevolution in strategic planning.

Stakeholder dialogue and alignment play a decisive role in shaping results. Evidence from the PortConstructor "Future Fuels" test sessions indicates that more frequent and transparent discussions correlate strongly with better-balanced outcomes in terms of People, Planet, and Profit. Conversely, ambiguity regarding stakeholder roles and insufficient communication frequently impedes progress, limiting the effectiveness of both port-led and shipowner-led strategies.

Underlying these dynamics are regulatory and policy frameworks that exert significant influence. Enforcement mechanisms, market-pull policies, carbon pricing, and subsidies collectively shape the feasibility and attractiveness of alternative fuel solutions. These instruments act as both catalysts and constraints, directly impacting investment decisions and the pace of maritime decarbonization.

Sub-Research Question 3: How do the interactions between ports and shipowners in a serious game simulation compare to real-world decision-making processes in the maritime fuel transition?

The serious game encapsulates multiple realistic facets of decision-making encountered in the maritime decarbonization landscape. It effectively mirrors the complex stakeholder dynamics characteristic of the sector, replicating the challenges of communication, coordination, and resource constraints frequently reported in practice. Participants consistently highlighted the difficulty of aligning divergent strategies and emphasized the critical necessity of a clear voice coupled with structured, purposeful dialogue.

Moreover, the game reflects the iterative nature of learning and adaptation inherent to real-world transitions. Just as stakeholders continuously refine their strategies in response to evolving insights on interdependencies, market conditions, and technological trade-offs, game players progressively evolved their approaches, demonstrating a deepening understanding of these complexities over time.

Financial constraints within the game imposed tangible limits on strategy formulation. The necessity to operate within budgetary boundaries compelled participants to move away from idealized plans toward pragmatically feasible options, paralleling real-world tendencies toward financial risk aversion and uncertainty surrounding capital investment.

Role ambiguity and reactive behavior also surfaced as prominent themes within the game. Ports were often perceived as reactive entities with fewer direct instruments than shipowners, an observation that aligns closely with the institutional realities of maritime governance and operational influence.

Central to both the game and supporting interviews was the recognition of knowledge exchange as a vital “learning mechanism”. Brining diverse stakeholders together to share information, surface assumptions, and critically examine prevailing perspectives was repeatedly underscored as essential for effective coordination and strategy alignment.

While the game operates within a compressed timeframe and necessarily simplifies some complexities inherent to maritime decarbonization, it nonetheless offers a valuable and robust model. It provides a practical environment to explore the long-term, systemic challenges involved in aligning strategies between ports and shipowners, facilitating engagement with the nuanced realities that define this multifaceted transition.

Main Research Question: How does the initiator of fuel transition decisions (port vs. shipowner) impact the success of decarbonization efforts in the maritime industry?

Port-led transitions frequently capitalize on the strategic roles that ports occupy as landlords, operators, regulatory authorities, and community stakeholders. These positions empower ports to drive technological deployment, develop critical infrastructure such as bunkering facilities for alternative fuels, and foster cross-sector collaboration essential for maritime decarbonization. While ports provide indispensable fuel infrastructure and management systems, they confront significant challenges including constrained budgets, environmental expenditure obligations, and the need for investments in workforce training. In port-led scenarios, decision-making tends to initially prioritize alternative fuels such as LNG and methanol, subsequently evolving toward increased emphasis on fleet renewal and vessel retrofitting as infrastructure and market readiness mature.

Conversely, shipowner-led transitions focus primarily on operational decisions centered around retrofitting existing vessels and renewing fleets, with considerations heavily influenced by cost efficiency, profitability imperatives, and competitive positioning. Shipowners generally respond to the availability of port infrastructure and prevailing market conditions, often adopting reactive strategies. Notably, early adopters within more profitable segments, typically those with newer fleets, demonstrate a greater propensity to embrace alternative fuels, whereas smaller operators frequently face financial and informational barriers that delay their transition.

The success of either transition pathway is fundamentally mediated by the quality of coordination and communication between ports and shipowners. Analysis of the serious game dynamics reveals that port-led transitions exhibit strategies closely aligned with infrastructure development and fuel availability, whereas shipowner-led scenarios emphasize asset-level optimizations such as retrofitting. These interaction patterns underscore that successful maritime decarbonization is less a function of which party initiates the transition and more contingent on cooperative alignment and ongoing stakeholder dialogue.

In summary, neither port-led nor shipowner-led transitions alone offer a sufficient framework for effective decarbonization of the maritime sector. Instead, success rests upon a well-coordinated, communicative partnership between ports and shipowners. While initiation by one party can shape the strategic focus, overcoming the persistent challenges of coordination, financial constraints, information asymmetries, and regulatory ambiguity, challenges well reflected in both the game outcomes and expert interview insights, are critical. Ultimately, gradual, iterative, and informed collaboration grounded in transparent dialogue fosters the most balanced achievement of environmental, social, and economic objectives within the maritime fuel transition.

5.2. Limitations of the Study

While the serious game and its associated analyses offer valuable insights into maritime decarbonization strategies, several limitations warrant careful consideration.

The game's simplified depiction of real-world dynamics necessarily abstracts complex technical, economic, and regulatory factors. Although this simplification supports stakeholder engagement and facilitated exploration of scenario-based decision-making, it inevitably omits certain nuances and externalities, which may constrain the generalizability of the findings.

The constrained decision-making timeframe and limited resources inherent to the game environment restrict the depth of strategic planning and curtail long-term foresight. Participants operated under realistic time pressures that simulate negotiation dynamics but may have limited the exploration of innovative or longer-term approaches.

The composition of the participant pool, along with their assigned roles, perspectives, and expertise, might shape observed outcomes. Despite deliberate inclusion of key stakeholders such as port authorities and shipowners, the exclusion of other influential actors, including regulators, fuel suppliers, and end customer, means that the modeled interactions and incentives do not fully capture the broader ecosystem influencing maritime decarbonization.

The technological pathways and fuel options presented reflect prevailing knowledge and assumptions, which are inherently provisional given rapid technological developments and shifting market conditions. This introduces uncertainty regarding the projected feasibility and attractiveness of specific interventions, including retrofitting strategies and infrastructure investments.

Finally, while cultural and organizational factors are acknowledged as critical to decision-making, their comprehensive quantification and modeling remain challenging within the game framework. Although stakeholder motivations and communication styles were qualitatively considered, integrating these dimensions robustly into strategic simulation tools would require more extensive empirical data.

In summary, the insights derived from this study should be interpreted with these limitations in mind. They underscore the necessity for complementary research methodologies and ongoing iterative validation to effectively refine maritime decarbonization strategies.

5.3. Future Research Suggestions

Building on the insights and limitations identified in this study, several avenues for future research emerged to further advance maritime decarbonization strategies.

Broadening the scope of stakeholder involvement to encompass regulators, fuel suppliers, and cargo owners, in addition to ports and shipowners, would offer a more holistic understanding of the ecosystem dynamics and incentive structures influencing decarbonization pathways. Such expanded inclusivity promises to enhance the realism and applicability of strategic modeling efforts.

The development of more sophisticated game frameworks or simulation tools that incorporate extended time horizons and greater resource flexibility would enable participants to engage in deeper explorations of innovative technologies and policy instruments. These improvements would facilitate testing of phased transition scenarios and allow stress-testing of strategies under varying and evolving market and regulatory conditions.

Cultural, organizational, and behavioral dimensions merit more systematic examination through both qualitative and quantitative methodologies. Gaining insight into how stakeholder motivations, communication patterns, and negotiation processes affect strategy adoption would inform the design of more effective engagement and facilitation practices.

Finally, the integration of environmental, economic, and social metrics into decision-support tools remains an essential research focus. Improving the usability and precision of these tools can better inform investment decisions and policy development, aiding the balance of sustainability objectives with profitability and operational efficiency.

Pursuing these research directions holds promise for iterative, evidence-informed enhancements in maritime decarbonization strategies, thereby supporting the emergence of a more resilient and sustainable shipping sector.

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Appendix 1: Questionnaire for players

You got an Excel file ("Calculation Assistant") sent to you via email. Use this to document you progress throughout the game. In the light-colored fields, enter what you are building/demolishing.

After the game:

- (before clicking on finish!!) Take a screenshot of your map
- Take a screenshot of your high score
- Save and send the excel file ("Calculation Assistant") to schmidt@ese.eur.nl

1. At which session did you participate?

   ☐ KVNR 16.05.

   ☐ Estonia 21.05.

   ☐ 26.05.

   ☐ 05.06.

   ☐ Other:

2. Do you have a maritime background?

   ☐ No

   ☐ Yes, ports

   ☐ Yes, shipping

   ☐ Other:

3. Have you ever played a serious game? (A game that is not solely for entertainment, but rather for educational purposes)

   ☐ No

   ☐ Yes

4. Which stakeholder role do you have in the game?

   ☐ Port

   ☐ Shipping

5. What do you think is the major challenge in the fuel transition in shipping? (open question)

6. Who took the lead in the transition during the gaming session?

   ☐ Port-led transition

   ☐ Shipowner-led transition

7. After hearing the presentation, what strategy did you choose? (multiple answers possible)

   ☐ Retrofitting with WAPS

   ☐ Retrofitting with CCS

   ☐ LNG

   ☐ Methanol

   ☐ Ammonia

   ☐ Fleet expansion

   ☐ Fleet renewal

   ☐ Other:

8. Why did you choose this strategy? (open question)

9. What are the 3 key takeaways of the stakeholder discussion(s)? (open question)

10. After the stakeholder discussion, how would you change your strategy? (multiple answers possible)

    ☐ No changes

    ☐ Retrofitting with WAPS

    ☐ Retrofitting with CCS

    ☐ LNG

    ☐ Methanol

    ☐ Ammonia

    ☐ Fleet expansion

☐ Fleet renewal

☐ Other:

11. Why would you (not) change your strategy? (open question)

12. How many stakeholder discussions were held?

☐ None

☐ 1 (before Round 1)

☐ 1 (after Round 3)

☐ 2 (1 before Round 1, 1 after Round 3)

13. What were your scores for People, Profit, Planet?

14. What was your High Score?

15. How successful do you think your strategy was?

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very successful

16. Why do you think your strategy was (not) successful and is there something you would do different next time? (open question)

Appendix 2: Market Overview

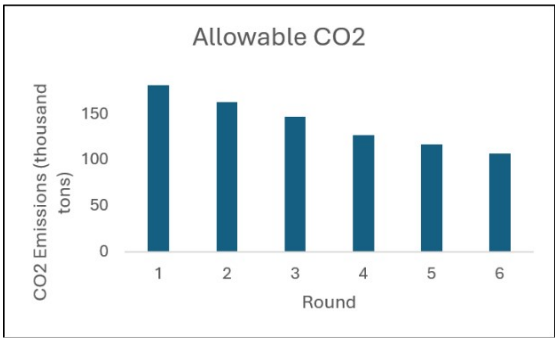

Figure 18 Allowable CO_2 (own work)

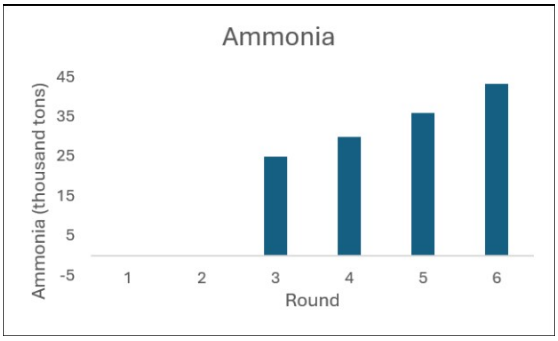

Figure 19 Ammonia Market (own work)

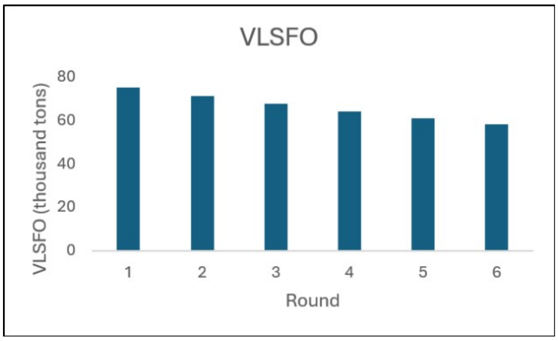

Figure 20 VLSFO Market (own work)

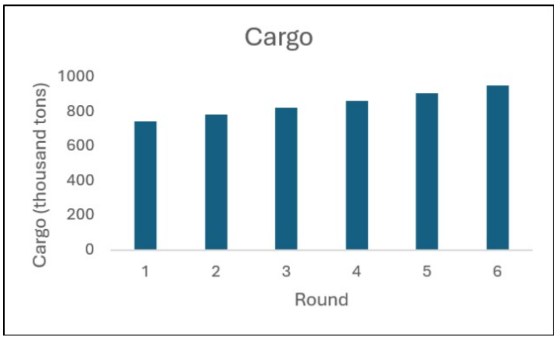

Figure 21 Cargo Market (own work)

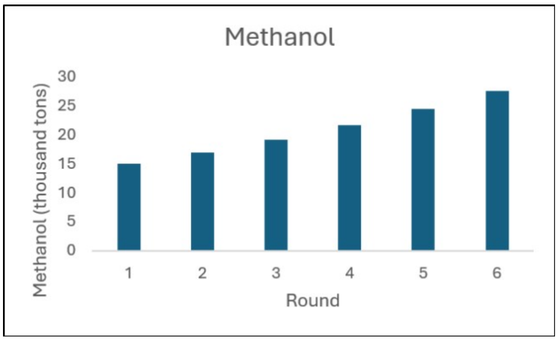

Figure 22 Methanol Market (own work)

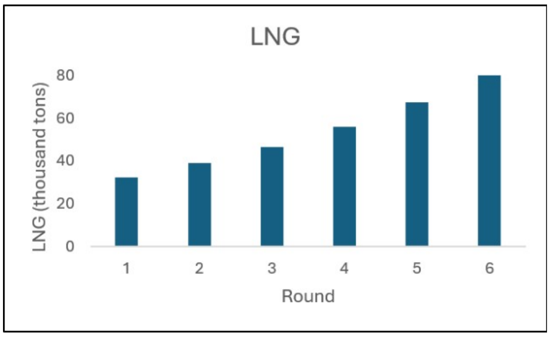

Figure 23 LNG Market (own work)

Appendix 3: Interview Overview

Interview	Interviewee	Function	Company	Date	Location
1	Jeroen Pruyn	Academic (shipping)	TUDelft	16.07.2025	Online
2	Annet Koster	Managing Director	KVNR	16.07.2025	At KVNR Office in Rotterdam
	Nathan Habers	Director Communications and External Affairs			
3	Francesca Morucci	Senior Representative in the Transparency, anti-corruption, training, and promotion department	Autorità di Sistema Portuale del Mar Tirreno Settentrionale (the North Tyrrhenian Port Network Authority)	24.07.2025	Online
4	Pratham Solanki	Port Finance and Strategy Consultant	MTBS	07.08.2025	Online

Table 7 Overview of Interviews (self-compiled)

Appendix 4: Categorization of Results into "Chicken-and-egg" Dilemma

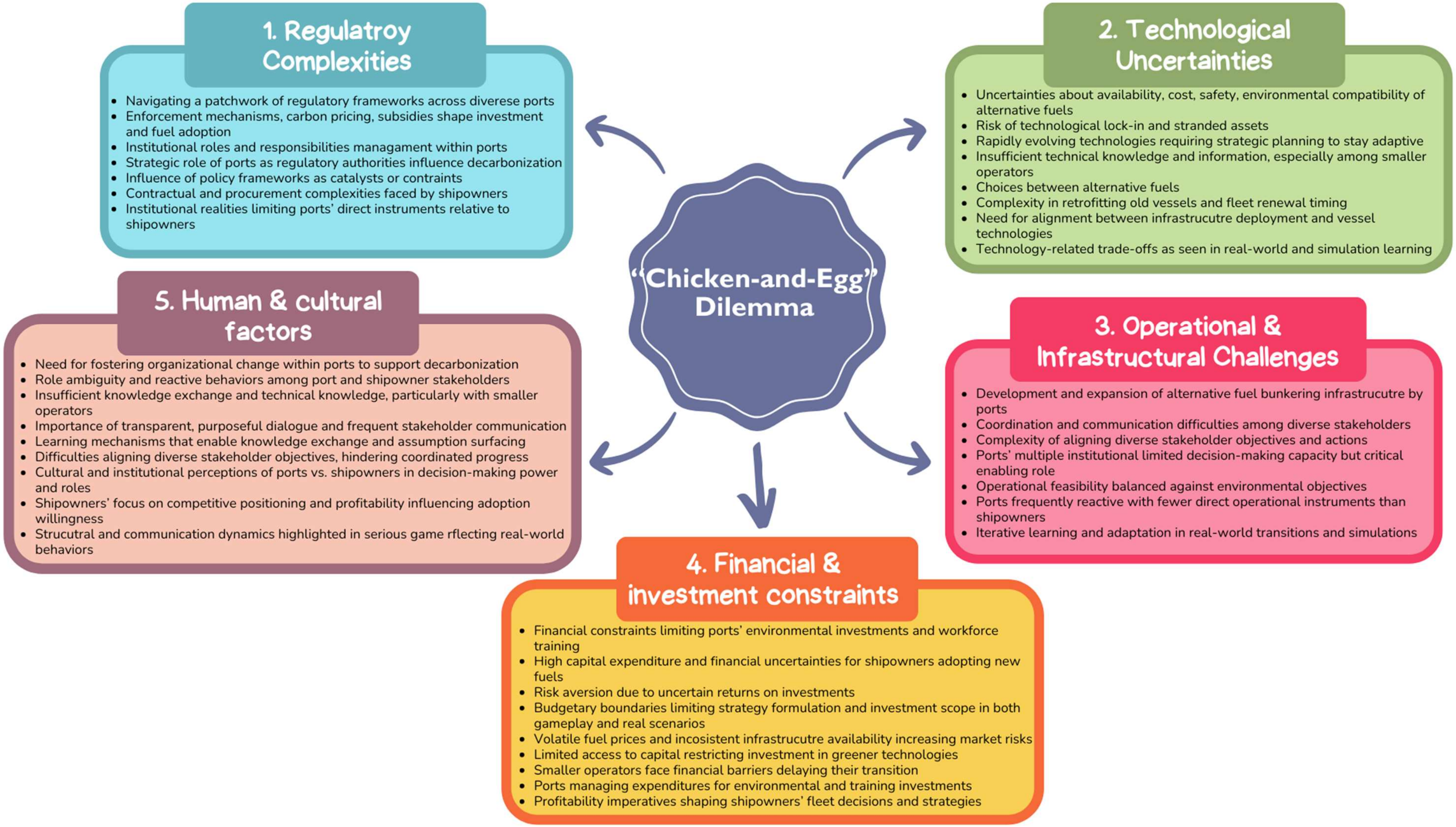

Figure 23 "Chicken-and-egg" Dilemma (own work)

Appendix 5: Game Teaser

PORT CONSTRUCTOR GAME: FUTURE OF FUELS

Port Constructor

Serious gaming can provide stakeholders valuable experience with strategic dilemmas. In collaboration with TU Delft, the Port of Rotterdam Authority, STC and InThere/MProof, Erasmus UPT developed a game platform where players can experience these strategic dilemmas. Port Constructor is a so-called microgame with missions, taking 15 to 20 minutes. Each one starting with a short strategy discussion and several rounds of action. The game can be played in combination with a workshop on stakeholder management, but also in a training course, and in class.

As a social innovation, the game contributes to a shift in thinking about the energy transition. Research shows that players better understand the complexities of the fuel transition. Addressing complexities often necessitates acknowledging the simultaneous consideration of opposing interests. In the context of shipping, this lies in achieving better environmental performance, while maintaining competitiveness. Stakeholders often demonstrate bounded rationality in their decision-making due to a lack of information, acceptable performance outcomes or insights into dynamics between influencing factors in the long-term. Port Constructor helps students and professionals to gain a better understanding.

Future of fuels

Shifting to alternatives for ship's propulsion for a large part is determined by the use of alternative fuels. The future of the fuel mix is however uncertain, with a highly unpredictable demand, and a limited availability of fuel and a wider range of fuel options. Why is it so difficult for shipping companies to decarbonize?

Financial Reasons	Supply and demand	Level playing field	Innovation
Capital intensity and long life cycle of ships	Availability fuel infrastructure, required for ships to bunker in trades where ships are deployed.	National governments protecting domestic industry	Technological solutions are advancing, with higher energy efficiency potential.
Alternative fuels are often more expensive	Uptake of alternative fuels by shipping companies (and other industries)	Fragmented regulatory framework with different standards	Adopting emergent technologies is often more expensive and drives up the operational costs

Game Map

PORT CONSTRUCTOR GAME

Aim of the game

To optimize the balance between three equally important value drivers: people, planet and profit. Based on a basic strategy, the player must consider how neighboring features affect each other, positively or negatively.

Gameplay

In this serious game, the player develops and manages a fleet or a port. The player chooses from a variety of options:

<table>
<tr><th>Maritime Side</th><th>Port Side</th></tr>
<tr><td>Building/Removing ships as functions to the shipping lines
Retrofitting ships with WAPS or CCS</td><td>Building port infrastructure to make alternative fuels available
Bunkering function Storage
function</td></tr>
<tr><th colspan="2">Steps in the development</th></tr>
<tr><td>1.Choose your fuel strategy (mono, dual, multi)
2.Choose how to adjust your fleet (newbuilding, retrofit)
3.Choose which port infrastructure to build attract</td><td>1.Choose your fuel strategy (mono, dual, multi)
2.Choose the port infrastructure
3.Choose which shipping companies to attract</td></tr>
<tr><td colspan="2">Market place to match demand and supply of fuel
Play the micro-game again, but now with a ‘marketplace’ mechanism, in which port and shipping
companies share information upfront and proactively.</td></tr>
</table>

Colophon & Contact

This game is developed by Erasmus University Rotterdam | Erasmus Centre for Urban, Port and Transport Economics for Erasmus Centre of Maritime Economics & Logistics, and other maritime institutes in The Netherlands.

Authors:
Maurice Jansen
Giuditta Schmidt

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