Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Lasse Killingmo

Optimal location of ammonia replenishment to support the Northeast Asia - US Pure Car Carrier green corridor

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2023

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Kunnskap for en bedre verden

Master Thesis in Marine Systems Design
Stud. Techn. Lasse Killingmo
"Optimal location of ammonia replenishment to support the Northeast Asia – US Pure Car Carrier green corridor."
Spring 2023

Background

Green shipping corridors have been recognized as one of several critical pathways to zero-carbon shipping. These corridors aim to accelerate a fair fuel and technology transition, introducing zero-emission ships and fuels across trade lanes. However, uncertainty is still related to how one can accelerate such corridors. Energy replenishment at strategic locations along the trade lanes may be an option that can support further development of maritime green corridors.

Overall aim and focus

The overall aim of the master thesis is to provide decision support to stakeholders in green shipping corridors by investigating optimal locations for energy replenishment for zero emission vessels.

Scope and main activities
The candidate should presumably cover the following main points:

1. *Present an overview of the green shipping corridor concept including possible deep-sea routes to be transformed into a green corridor.*

2. *A literature study on alternative low-emission fuels, including fuel families, energy carriers, converters, and replenishment strategies.*

3. *Present relevant methods within operation research and applicable optimization models for optimal location of energy replenishment locations.*

4. *Introduce a mathematical optimization model for optimal placement of energy replenishment locations.*

5. *Extend and apply the model presented in 3 on a realistic case study of the transpacific, Northeast Asia- US Pure Car Carrier corridor.*

6. *Discuss and conclude.*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. The work shall follow the guidelines given by NTNU for the MSc Master work.

Stein Ove Erikstad
Professor/Responsible Advisor

Abstract

Approximately 80 % of global trade is carried by sea. Deep-sea shipping ensures the most cost-effective transport of manufactured goods and significantly impacts the world economy. However, maritime transportation currently accounts for 3 % of global greenhouse gas (GHG) emissions and will be required to reduce emissions in line with the global climate strategy. The transition from a carbon-reliant industry to one that operates without significant emissions constitutes a major challenge. Such a transition will necessitate a multi-dimensional, multi-stakeholder, and multi-technological development process supported by various global regulations. In this context, green shipping corridors have emerged as a measure to accelerate the transition, where a green corridor refers to a major shipping route along which low- and zero-carbon maritime transportation solutions are provided. However, the concept is relatively immature, and research into how such corridors can be accelerated will be required.

In this thesis, we investigate the option of performing energy replenishment to accelerate green shipping corridors by designing a network of onshore and offshore replenishment sites that can support alternative fueled vessels making the transpacific route between Northeast Asia and the US. Moreover, a mathematical optimization model to identify the optimal sites for energy replenishment is introduced and applied to the network.

Pure car carriers (PCC) are selected as the vessel segment to target, as it is considered a segment with a smaller number of vessels, operators, and shipping customers, all critical factors that may increase the feasibility of a green corridor. Moreover, we choose ammonia as the preferred energy carrier, which has received considerable attention as a carbon-free energy carrier. However, ammonia is roughly half as energy dense by weight as heavy fuel oil (HFO) and approximately 50 percent more voluminous. For these reasons, the fuel tanks currently located in the ship's void space would need to be increased, introducing a lost opportunity cost due to lost cargo space, which is significantly more influential in the PCC segment than other shipping segments, such as containers or dry bulk.

Results from the case study show that energy replenishment at strategic locations can be an attractive solution for accelerating the deployment of ammonia-fueled PCC vessels sailing between ports in Northeast Asia and the US. Our findings show that the underway replenishment of ammonia can be a viable solution to the required increase in fuel tank size, as several of the investigated scenarios revealed a reduced energy storage capacity by performing energy replenishment en route. However, there is a significant variation in the required volumes obtained from the case study, and such findings imply further investigation into fuel tank sizes and connecting machinery systems. Additionally, we discover that energy replenishment can occur at strategic onshore and offshore locations. Under certain circumstances, combining these two will be optimal if the correct preconditions exist. Dutch Harbour and Hawaii could be critical strategic locations in a transpacific energy replenishment network, serving not only as sites for energy production but also for energy replenishment and fuel distribution to other replenishment locations in the network. It is also revealed that the model can handle independent offshore replenishment sites. However, such a solution should only be considered feasible in a longer time perspective.

The work performed through this thesis proposes a logistical energy replenishment network as one of several alternative measures for a successful Northeast Asia-US green corridor. It provides information that can be used to make decisions about future green shipping corridors worldwide. Regardless of our findings, the route must demonstrate further success in adopting alternative fuels, coordinated action among stakeholders, and regulatory support on both sides of the Pacific Ocean. It is a difficult task that can be completed under the right conditions.

Sammendrag

Skip er regnet som den mest kostnadseffektive metoden for frakt av varer rundt om i verden. Omtrent 80 % av den globale verdenshandelen foregår i dag på sjøen og denne formen for transport er i stor grad drevet på tungolje, diesel og andre miljøfiendtlige fossile drivstoff. Dette gjør at global skipsfart i øyeblikket står ansvarlig for rundt 3 % av globale CO_2 utslipp. I likhet med andre industrier vil også skipsfarten være nødt til å omstille seg for å kunne imøtekomme de globale klimamålene. Overgangen fra en karbonavhengig industri til en som operere uten betydelig utslipp er en enorm utfordring. En slik overgang vil kreve en flerdimensjonal utviklingsprosess støttet opp av globale forskrifter og regelverk. I den forbindelse har konseptet grønne skipskorridorer blomstret opp som et sentralt tiltak for å få fart på overgangen fra fossilt til alternativt drivstoff og dermed den grønne skipsfarten. Grønne skipskorridorer er spesifikke strekninger hvor det legges til rette for overfart med null utslipp. Dette gjøres ved at offentlige og private aktører samarbeider om å tilgjengeliggjøre nødvendig infrastruktur som bunkeringsterminaler og utslippsfrie drivstoff. Konseptet er relativt nytt og metoder og strategier for hvordan slike korridorer kan akselereres vil være nødvendig å undersøke i tiden fremover.

Denne masteroppgaven undersøker muligheten for etterfylling av drivstoff underveis på en seilingsrute som et alternativt tiltak for å akselerere grønne skipskorridorer. Dette gjøres ved å utforme et nettverk av land- og havbaserte lokasjoner der skip drevet av alternative drivstoff kan stoppe innom for å etterfylle drivstoff mellom havner i Nord-Øst Asia og vestkysten av USA. Videre introduseres en matematisk optimeringsmodell som har som formål å identifisere de optimale lokasjonene i nettverket. Dedikerte bilfrakteskip er valgt som det foretrekkende skipssegmentet for videre undersøkelse. Dette har sin begrunnelse i at bransjen omfatter relativt få skip, få aktører og få kunder. Dette er gode egenskaper som kan bidra til økt sannsynlighet for etableringen av en grønn korridor. Samtidig velges ammoniakk som det foretrekkende alternative drivstoffet og utruste disse skipene med. Dette er i hovedsak motivert av økt oppmerksomhet rundt denne typen energibærer for bruk i skipsfarten. Samtidig er ammoniakk omtrent halvparten så energitett som vanlig dieselolje og den vil dessuten kreve dobbelt så mye volum. Slike egenskaper vil føre til at drivstofftankene vil måtte øke i størrelse, som igjen vil føre til en tapt kostnad som følge av at skipene vil kunne frakte færre biler. En slik kostnad vil være spesielt innflytelsesrik for bilfrakteskip sammenlignet med andre skipssegmenter.

Resultatene fra case studien viser at etterfylling av drivstoff på strategiske lokasjoner er et attraktivt tiltak som kan bidra til å akselerere en grønn stillehavskorridor der ammoniakkdrevede bilfrakteskip seiler mellom havner i Asia og USA. Våre funn indikerer at etterfylling av drivstoff i mange tilfeller kan løse problemene relatert til større drivstofftanker. Dette kan underbygges ved at vår studie viser en reduksjon i påkrevd energilagringskapasitet ved å gjennomføre etterfylling underveis, i flere av scenarioene som er undersøkt. Samtidig kommer det frem at de påkrevde lagringsvolumene varierer i stor grad fra scenario til scenario. Derfor vil det være naturlig at videre undersøkelse fokuserer på hvilke tankstørrelser det vil være fornuftig å benytte. Parallelt med disse funnene er det også oppdaget at etterfylling av drivstoff vil kunne gjennomføres, både til lands og til havs. Under de riktige forutsetningene er til og med en kombinasjon av landbaserte og havbaserte etterfyllingslokasjoner en optimal løsning. Det avdekkes også at Dutch Harbour og Hawaii kan vise seg og bli svært strategiske områder for etterfylling av drivstoff, men også for produksjon og distribusjon av drivstoff til andre optimale lokasjoner.

Arbeidet utført i denne masteroppgaven vil gi verdifull informasjon som kan brukes til å ta beslutninger om fremtidige grønne skipskorridorer. Uavhengig av våre funn, må korridoren fortsatt vise ytterligere suksess i forhold til alternative drivstoff, koordinert handling blant interessenter og regulatorisk støtte. Det er en kompleks oppgave som kan gjennomføres med de rette tiltak.

Preface

The following Master Thesis marks the end of my Master of Science degree in Marine Technology with a specialization in Marine Systems Design. The thesis was written at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) during the spring of 2023. The workload is equivalent to 30 ECTS. Parts of the work are based on a pre-project written in the fall of 2022. This mainly concerns a literature study on green shipping corridors, ship fuel pathways, and the car carrier market.

Trondheim, Norway, June 2023

Lasse Killingmo

Acknowledgments

First, I would like to thank my supervisor, Professor Stein Ove Erikstad (NTNU), for many good discussions and invaluable guidance throughout the semester. I'd also like to acknowledge Andreas Breivik Ormevik (Phd Candidate at NTNU, Department of Industrial Economics and Technology Management) for taking the time to discuss operation research and mathematical model development aspects in my master thesis.

Thanks should also go to professionals within the maritime industry. Special thanks to Øyvind Endresen (DNV) and Gunnar Koløen (Gram Car Carriers) for providing me with many references on green shipping corridors and the car carrier market, which has been very useful throughout the work with this thesis.

Thank you!

Lasse Killingmo

Table of Contents

List of Figures

List of Tables

Abbreviations

AFI Alternative Fuel Insight platform.

CAPEX Capital Expenditure.

CCS Carbon Capture and Storage.

ceu car equivalent units.

CFD Contract for Difference.

ETS European Trading System.

FAME Fatty acid methyl ester.

FLP Facility location problem.

FRLM Flow refueling location model.

G-VRP Green Vehicle Routing Problem.

GHG Greenhouse Gas.

HFO Heavy Fuel Oil.

HVO Hydro-treated vegetable oil.

ICE Internatl Combustion Engine.

ICS International Chamber of Shipping.

IMO International Maritime Organization.

LNG Liquid Natural Gas.

LPG Liquefied petroleum gas.

LSFO Low Sulphur Fuel Oil.

MGO Marine Gasoil.

mmBtu British thermal unit.

MSR Molten Salt Reactor.

NO_x Nitrogen Oxide.

OR Operation research.

PCC pure car carrier.

PEMFC Proton exchange membrane fuel cells.

PM Particular matter.

PTS Port-to-Ship.

SO$_x$ Suplhur Oxide.

SPP Shortest path problem.

STS Ship-to-Ship.

TCO Total Cost of Ownership.

TSP Traveling salesman problem.

TTS Truck-to-Ship.

UN United Nations.

UNREP Underway replenishment.

VLCC Very large crude carrier.

VLSFO Very Low Sulphur Fuel Oil.

VRP Vehicle routing problem.

WMO World Meteorological Organization.

Chapter 1

Introduction

1.1 Background

Global CO2 emissions and their impact on the planet have been high on the agenda for over a decade, and their relevancy will continue to exist for years to come as the world is currently not on track to meet the global climate goals. The 2022 version of The United Nations (UN) World Meteorological Organization (WMO) report revealed that the past eight years are on track to be the eighth warmest on record, fueled by ever-rising greenhouse gas concentrations and accumulated heat (WMO 2022). Such devastating reading will see the need for immediate and profound emission reduction across all sectors and regions, including the shipping industry.

Maritime transportation plays a vital role in the global economy, serving as the primary means of international shipping and comprising a significant percentage of the world's seaborne trade. According to data from the United Nations Conference on Trade and Development UNCTAD (2022), maritime transportation accounts for approximately 80% of global trade by volume. This mode of transportation encompasses a diverse range of activities, including the carriage of goods by sea, fishing, tourism, the exploration and exploitation of marine resources, the extraction of minerals from the sea, and scientific research. These activities facilitate the movement of goods and resources across the globe and contribute to the livelihood of individuals and communities worldwide. Considering energy use per mile traveled, marine transportation demonstrates significantly higher efficiency than other available transportation modes. However, due to the massive global trade scale, ships are responsible for about 3% of annual global Green House Gas (GHG) emissions and 9% of global emissions associated with transportation. The world fleet has also seen continuous growth in the last decades, with an average annual growth rate of 2,49% between 2013 and 2018. The general trend indicates that vessels categorized as large and very large ships are increasing the most, pushing an average annual growth rate of 25%. Such ships are responsible for about 85% of net GHG emissions associated with the international shipping industry (IRENA 2021).

The transition from a carbon-reliant global shipping industry without GHG emissions constitutes a significant challenge. The transition will necessitate a multi-dimensional, multi-stakeholder, and multi-technological development process that must be guided by a range of mutually reinforcing global regulations (WSC 2023). In response to the Paris Agreement of 2015, aiming to limit global warming to well below 2, preferably 1,5 degrees Celsius compared to industrial levels (UN n.d.), the International Maritime Organization (IMO) established its initial strategy in 2018, driving policy development in international shipping. The objective is to strengthen IMOs contribution by addressing GHG emissions from international shipping. At the same time, acknowledge the critical role of the industry and the impact on states and identify and implement measures to help achieve such objectives. Two ambitions have also been developed, including reducing CO_2 emissions per transport work by at least 40% by 2030, pursuing efforts towards 70% by 2050 using 2008 as the base year, and peak GHG emissions from international maritime transportation as soon as possible, aiming for a 50% reduction by 2050 (IMO 2018). In the wake of IMOs initial strategy, discussions regarding the level of ambitions set by the institution have emerged. The ambitions appear outdated compared to the global goal of achieving net zero by 2050. Several stakeholders, including the International Chamber of Shipping (ICS), representing national shipowner organizations and more than 80% of the global shipping industry, reinforce such a statement. ICS support a 2050 net zero target and are pushing the IMO and governmental institutions worldwide to incorporate it into their regulatory framework.

To meet the ambitious net zero target, ICS expects thousands of new zero-emission vessels to be deployed within 2030 (International Chamber of Shipping 2021).

Green shipping corridors have been recognized as one of several critical pathways to zero-carbon shipping. These corridors aim to accelerate an impartial fuel and technology transition, introducing zero-emission ships and fuels across trade lanes where necessary infrastructure is available. However, the concept still needs to be developed, which has led to questions about how one can emerge approaches to defining, initiating, and governing maritime green corridors. To further accelerate the concept, relevant stakeholders must investigate multiple options to enable vessels to operate on low- and preferably zero-carbon fuels. Energy replenishment at strategic locations along the trade lanes may be one such option.

1.2 Objective

The following master thesis aims to provide decision support to stakeholders in green shipping corridors by investigating optimal locations for energy replenishment for zero-emission vessels.

To investigate the potential of energy replenishment in green shipping corridors, the following points will be covered in this thesis:

1. Present an overview of the Green Shipping Corridor domain, including stakeholders, requirements, and barriers to overcome. The most promising trade routes are also introduced.

2. Provide a literature study on alternative low-emission fuels, including fuel families, energy carriers, converters, and replenishment strategies.

3. Present relevant methods within operation research and applicable optimization models for solving optimal location of energy replenishment sites.

4. Introduce a mathematical optimization model for optimal placement of energy replenishment locations.

5. Extend and apply the model presented in 3 on a realistic case study of the transpacific, Northeast Asia – US corridor.

6. Present the results from the case study.

7. Discuss and conclude.

1.3 Approach

The approach utilized in this thesis to investigate the optimal location of energy replenishment as a measure for accelerating green shipping corridors divides into two parts. First, we introduce the concept of green shipping corridors through a literature study, including an in-depth review of alternative fuel pathways, technologies, and energy replenishment strategies. Secondly, operations research as decision support for zero-emission vessels operating in green corridors is investigated through a mathematical optimization model for optimal placement of energy replenishment locations. Finally, the model will be applied to a proposed green corridor through a case study.

1.4 Structure of the thesis

This master thesis consists of 10 chapters and is structured as follows:

- **Chapter 2** - Introduces the concept of green shipping corridors by establishing a corridor domain. Aspects such as definitions, stakeholders, functions, and requirements are being addressed, and critical barriers to overcome.

- **Chapter 3** - Provides an overview of fuel families, energy converters, and alternative energy carriers that can be installed on vessels operating in green corridors. Strategies for energy replenishment are also introduced.

- **Chapter 4** - Introduce relevant theory, central methods, and models within operation research.

- **Chapter 5** - Presents two initial mathematical optimization models for the optimal location of energy replenishment.

- **Chapter 6** - Introduce an expansion of the initial models presented in Chapter 5 to comply with a realistic case study.

- **Chapter 7** - Introduces a case study of the North East Asia - US green corridor where the model presented in chapters 5 and 6 are utilized.

- **Chapter 8** - Presents the results from the case study.

- **Chapter 9** - Provides a discussion of the results from the North East Asia - US green corridor case study, in addition to other relevant topics.

- **Chapter 10** - Presents the conclusion of the thesis, and proposes further work.

Chapter 2

Green shipping corridors

Green shipping corridors are a new label that has entered the shipping industry. Such corridors could become critical enablers for the uptake of zero-emission fuels and, thus, shipping decarbonization. The following chapter comprehensively overviews the green corridor domain by emphasizing emerging activities and the most promising routes, definitions, and approaches. Key stakeholders and possible barriers to overcome will also be presented.

2.1 Emerging corridors

In the wake of the Clydebank Declaration of 2021 - where the signatories of the Declaration are to support the establishment of green shipping corridors, several initiatives, partnerships, and studies have already been established. According to Global Maritime Forum (2022a), as of 1 June 2022, eight announcements have been made covering collaborations and initiatives between the maritime industry, third-party sectors, and governments. The activities are taking place on different levels with corridor proposals on local, regional- and trans-ocean waters. Figure 2.1 illustrate the current ongoing projects on green shipping corridors.

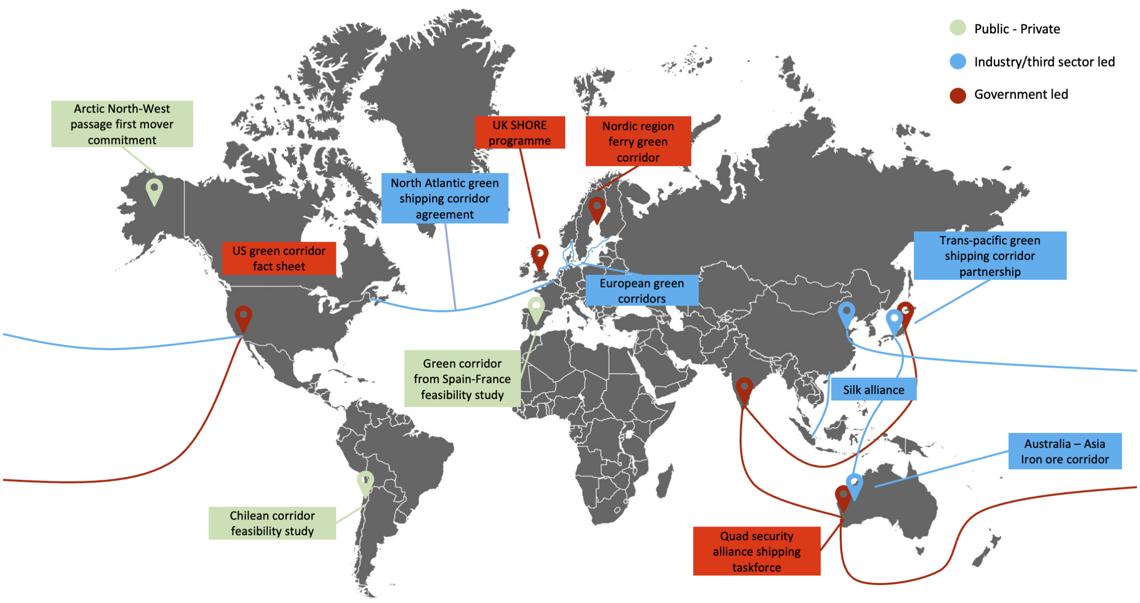


Figure 2.1: Initial initiatives on green shipping corridors (Global Maritime Forum 2022a).

2.1.1 The most promising routes

As seen in Figure 2.1, the maritime industry has proposed numerous maritime green corridors. However, only two corridors have been undertaken by pre-feasibility studies, namely the Australian - Japan iron ore and Asia-Europe container routes. Additionally, Northeast Asia - US car carrier corridor has been proposed as a route that can become a green corridor. These three routes cover major trade lanes between continents and are critical to decarbonize. Figure 2.2 presents the routes and the optional connecting ports.

(a) Australian-Japan iron ore route (b) Asia-Europe container route (c) Northeast Asia-US route

Figure 2.2: Three of the most promising green corridors (Global Maritime Forum et al. 2021).

The transport of iron ore between Australian mines and Japanese steelmakers reveals several advantages that could support the development of a green corridor. Such a route is expected to demonstrate hydrogen availability and accelerate partnerships between miners, vessel operators, and fuel producers. Additionally, it is discovered that the route could result in costs and benefits of zero-emission fuel transferred between fuel purchasers and other market participants, which can lead to mobilized demand for green shipping on the corridor (Global Maritime Forum et al. 2021).

The Asian-Europe container route is one of the longest trade routes a container vessel can make. However, This route is generating far more greenhouse gas (GHG) emissions than any other trade route in the world. Nevertheless, the route demonstrates favorable conditions for becoming a green corridor. The uptake of hydrogen projects in Europe, the Middle East, and Australia is estimated to be more than enough to serve the demand in the corridor. Moreover, the pre-feasibility study reveals that the demand for decarbonization across the value chain has increased, and it is reasonable to expect that such circumstances will leverage freight forwarders, consumers, and shipping companies. In addition to hydrogen, alternative fuels, such as methanol and ammonia, are also expected to be deployed on the route, giving vessel owners numerous alternatives when selecting their energy carrier (Global Maritime Forum et al. 2021).

The trans pacific Northeast Asia-US route has not yet been properly analyzed. Research into alternative fuels, collaborative incentives, and ports remains to strengthen the corridor proposal. Pure Car Carriers (PCC) vessels are an optional segment to target. However, a significant amount of research remains to conclude whether such a corridor can be considered feasible.

2.2 Definitions and nuances

A Green shipping corridor can be defined in several ways. Different institutions have defined and described the label with different perspectives and approaches, resulting in no fixed definition. Global Maritime Forum et al. (2021) emphasized the definition of a Maritime Green Corridor as *"pecific shipping routes where the technological, economic and regulatory feasibility of the operation of zero-emission ships is catalyzed by a combination of public and private actions"* in 2021. This definition has influenced and continues to affect other definitions in use. However, since new definitions have emerged, a review of the nuances and emphases can help provide clarity of the concept. Global Maritime Forum (2022b) present several definitions and nuances in their discussion paper on green corridors. The definitions divide into three different perspectives:

Perspective 1: Scalable end-to-end pilots driven by full value chain collaborations

- *"Zero-emission route between two or more ports"*. Defined through the Clydebank declaration.
- *"A green corridor covers the entire value chain supporting production, bunkering and vessel operations for an individual green fuel"*. Stated by Oxford research and the Technical University of Denmark (DTU).
- *"Green Corridors provide large-scale demonstrations of zero-carbon shipping that can push the industry to reach the tipping point of 5% uptake of zero-carbon fuels by 2030"*. Proposed by Lloyds Register.
- *"Maritime routes between two or more ports on which vessels are running on scalable zero-emission energy sources are demonstrated and supported"*. Proposed by the UK government and based on proposals from Global Maritime Forum.

Perspective 2: Enabling ecosystem/special economic zones at sea

- *"A shipping route between two major port hubs on which the technological, economic, and regulatory feasibility of the operation of zero-emission ships is catalyzed through public and private actions"*. Developed from Global Maritime Forum et al. (2021).
- *"Specific shipping routes where the economics, infrastructure, and logistics of zero- or near-zero emission shipping are more feasible and rapid deployment can be supported by targeted policy and industry action"*, Also developed from Global Maritime Forum.

Perspective 3: Low/zero emission routes

- *"Reduce greenhouse gas emissions from the movement of cargo on a given route"* Stated by the C40 group.
- *"Maritime routes that showcase low- and zero-emission lifecycle fuels and technologies with the ambition to achieve zero greenhouse gas emissions across all aspects in support of sector-wide decarbonization no later than 2050"*. Proposed by the US Government.

2.2.1 Defining "green"

To better understand green shipping corridors, insight into what we mean by "green" can be helpful. The term "green" can be approached in several ways, resulting in differences and stakeholders needing to decide what approach to apply to the concept. One crucial aspect is whether stakeholders prefer to define "green" through an emission-centric or technology-centric approach. An emission-centric approach defines "green" by emphasizing the potential to reduce emissions on given routes. Such an approach can connect emission reduction from deep-sea vessels to other, potentially short-term, emission sources such as port operations and full-chain logistics. On the other hand, a technology-centric approach evaluates "green" by emphasizing the demonstration and deployment of zero-emission technologies such as low-emission fuels, vessels, and infrastructure. As opposed to the emission-centric approach, this approach has been more commonly used. It addresses the urge for a targeted and coordinated technology demonstration as an enabler for long-term, large-scale decarbonization of the shipping sector.

2.2.2 Approaching the concept of a "corridor"

Providing clarity about what a corridor should strive to encompass is also necessary, and several approaches exist to define green corridors. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022) presents three approaches in their feasibility phase blueprint: single-point, point-to-point, and network-based corridors. As illustrated in Figure 2.3, single point corridors establish zero-emission shipping routes around a specific location, i.e., a port hub allowing round-trip bunkering. Point-to-point corridors are single routes between two ports. Such corridors target niche segments and are often based around a commodity transportation route. Network corridors establish routes between three or more ports, creating networks where vessels can operate on alternative fuels.

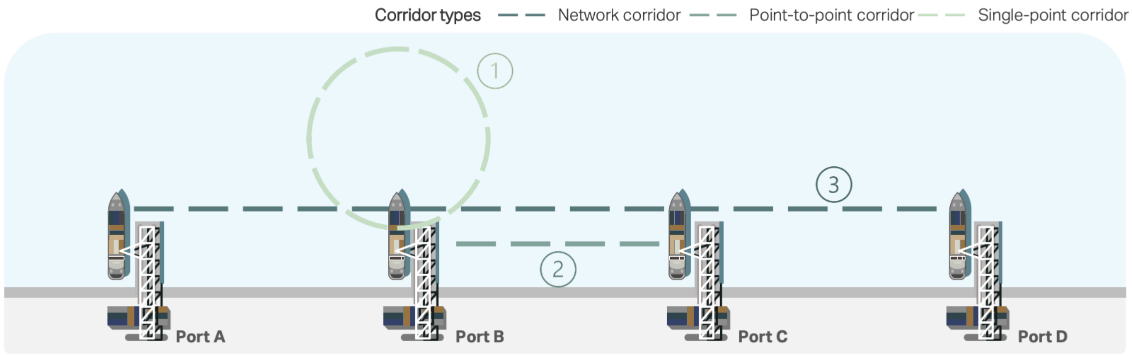


Figure 2.3: The main corridor types (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2022).

Figure 2.3 illustrate three different corridors centered around a port-centric approach. Such an approach puts the ports in the center of the system. Decisions on what activities to decarbonize, system boundaries, voyages, relevant cargo, and technologies will rely on the ports' priorities. A port-centric approach usually sets the system boundary at the port gates, resulting in operations and cargo handling being in scope. However, other approaches can be utilized. Global Maritime Forum (2022b) presents three alternative approaches in their discussion paper on green corridors.

Some corridors are less likely to be driven by ports. A route-centric approach centers around a specific route, focusing on the strategic interest of stakeholders involved in the corridor. An example of a route-centric corridor is the iron-ore green corridor between Australia and Japan. The route builds on the strategic interests of companies and stakeholders in the iron and steel value chain but also on the energy strategy of Australia and Japan. Vessels sailing on the route will likely be able to bunker in Australia alone, resulting in a focus area centered on making fuel supply and charter arrangement economics work.

Green corridors can also be approached by prioritizing direct investment in end-to-end pilots and scalable demonstration projects demonstrating zero-emission shipping capability. Such pilots must demonstrate the whole value chain in operation and can generate learning and build confidence in technologies. However, such pilots are not necessarily capable of being duplicated. If the pilots are constructed as a one-off project scaling and replicating will be challenging.

In contrast to the pilot and demonstration approach, a programmatic, niche market approach can be utilized. Such an approach focuses the corridor on developing conditions for multiple actions, pilots, and demonstrations, and in the end, to enable a full-scale operation. An essential aspect of the strategy is focusing on developing and maintaining an enabling environment rather than on any demonstration. Port-led initiatives such as the LA to Shanghai and Montreal to Antwerp routes are programmatic. At the same time, the type of support from governments committed to supporting green shipping corridors is yet to be decided. There has yet to be a clear answer to whether governments will directly support pilot- and demonstration projects or focus on supporting the enabling program through policies, guidance, open invitations, and funding.

Approaching green corridors differently will be a natural outcome due to different initiative-takers and governmental structures. However, in general, some guidelines should be emphasized. To promote scalability and learn about the concept, a programmatic approach focusing on the ecosystem will be a good strategy. In addition, it is crucial to emphasize overcoming obstacles and challenges that critical stakeholders such as shipowners, cargo-owners, and charterers are facing rather than a narrower emphasis on infrastructure and technology.

2.3 Stakeholders

A critical success factor for green corridors is engaging crucial stakeholders. However, it is important to emphasize that every green corridor has its own set of stakeholders, often dependent on the cargo transported. Nevertheless, there will be some fundamental stakeholders present in any corridor. Green corridors aim to facilitate the transportation of goods and cargo from point A to point B with as low CO2 emissions as possible. Accomplishing such a task requires coordinated action between numerous stakeholders. Figure 2.4 highlights several of the most common stakeholders in a green corridor and are based on the following important elements:

For cargo vessels to even sail at sea in the first place, there must be a transportation demand. Such demand calls for introducing stakeholders such as cargo owners and the end consumer. Cargo owners are starting to choose transportation methods with low carbon footprints. Such initiatives arise from their decarbonization ambitions but can also occur due to pressure from their related stakeholders, such as financial institutions. Cargo owners aiming to reduce their product life cycle emissions can therefore take advantage of low-carbon and zero-emission vessels operating as a part of a green corridor. It is also logical to predict that as more end customers choose environmentally friendly transportation methods, the expense of Eco-friendly green-labeled items will be passed on to downstream end consumers willing to pay a premium for green transportation.

Zero-emission vessels must be deployed to meet the demands of cargo owners and end users. It will introduce stakeholders like shipowners, vessel operators, shipbuilders, engine suppliers, and fuel storage systems suppliers. Shipowners and vessel operators will serve as the most prominent stakeholders in cargo transportation at sea. However, investing in low- and zero-emission vessels will involve other vital stakeholders like shipbuilders, engine suppliers, and fuel storage system suppliers. Vessel operators and charterers with operational control can also benefit from being a part of green corridors as it will help reduce their carbon footprint and reach their net-zero emission goals.

Without alternative fuels, zero-emission vessels will not be a reality. For access to bunkering, such fuels must be made available inside port gates or at strategic points along the corridor. Alternative fuels will bring critical stakeholders such as fuel suppliers and feedstock suppliers to the table. There is no clear winner when it comes to alternative fuels. Several scenarios and fuel pathways, however, are being proposed. Green corridors will benefit marine fuel producers and suppliers by ensuring long-term demand and allowing them to plan and implement strategies to rewire their production process. Green corridors and related funding may also leverage traditional fuel suppliers and manufacturers to transition to alternative fuel production.

Vessels transporting cargo at sea rely on more than just alternative fuels. Sufficient land areas where the cargo can be effectively offloaded for further transportation and movement up the value chain will also be required. Port logistics and bunkering infrastructure will necessitate participation from stakeholders such as port operators, bunkering suppliers, and fuel storage system providers. Ports that want to be first movers can benefit from green corridors because it will require them to upgrade their infrastructure and upscale from a regional hub to an international port hub.

Green corridors will require financial and regulatory support. The support must come from global, regional, national, and local regulatory institutions. Financial institutions like banks and debt providers will also be connected to green corridors as they will serve as enablers for developing incentives and collaborations of stakeholders previously described in this chapter. Finally, we highlight class societies as essential stakeholders as these institutions must approve the vessels operating on the corridors.

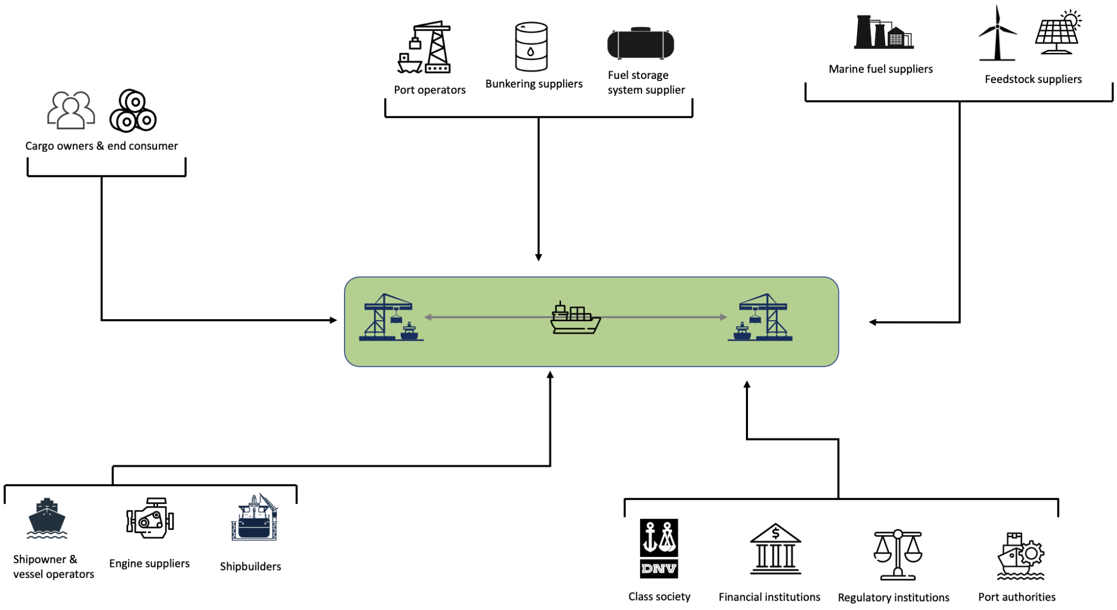


Figure 2.4: Important stakeholders in green shipping corridors.

2.4 Conditions conducive to the establishment of green corridors

The initial selection process of a green shipping corridor is a complex and demanding task. It will require a specific trade route to demonstrate a potential to decarbonize. It should also display the necessary impact to assist shipping in achieving its decarbonization goals. Such efforts will also need to be feasible from an implementation point of view. Decisions must be based upon real-world data that has experienced a rigorous review. Every alternative must go through a detailed pre-feasibility study, answering some critical questions.

Defining the green corridor's vision and goals will be a natural starting point. It will then be essential to establish an end goal for the corridor's key performance indicators (KPI) to gain insight into the monitoring measures. Following the KPIs, a timeline for the corridor formation must be developed. Will the corridor be operational within five years, or is it more realistic to expect a fully functional corridor in ten years? Furthermore, a regulatory framework must be present. It will lead to questions regarding whether such a framework is in place to support a green corridor at a country, region, city, or port level. If this is not the case, research into supporting measures for creating an enabling environment must be performed.

Establishing a business case will also be necessary. Identifying such cases and the timeline for the Return On Investment (ROI) will be an important area of focus. Funding is another perspective highly relevant. Revealing the funding sources and whether governmental support is available will be required. Green corridors are massive projects, and governmental support is crucial. This condition is particularly relevant in the port and bunkering infrastructure-green corridor interface (American Bureau of Shipping 2022).

A clear understanding of the stakeholders and members of the green corridor will also need to be in place. Who are the members of the establishments? Do we include all stakeholders introduced in Chapter 2.3, or can some be overlooked? Revealing the low and zero-emission fuel options and the scalability of these fuels will also be essential. Some final considerations should be about trade routes, cargo types, and vessel segments operating between ports that are a part of the green corridors. When these questions are addressed, a viable green corridor will reveal itself, including location, business case, members, and funding source.

2.5 Green corridors foundational requirements

A set of elements clearly and methodologically addressed is vital for green corridors, both for a successful development process and for a corridor's continued existence. Establishing foundational building blocks will ensure a successful launch of any corridor while mitigating possible risks (American Bureau of Shipping 2022). Several strategies can be utilized to define the foundational requirements and may vary based on the specifics of the corridor. However, a broad emphasis should center on *cross value chain collaboration*, *viable fuel pathways*, *shipping and logistical case*, and *policy and regulation*.

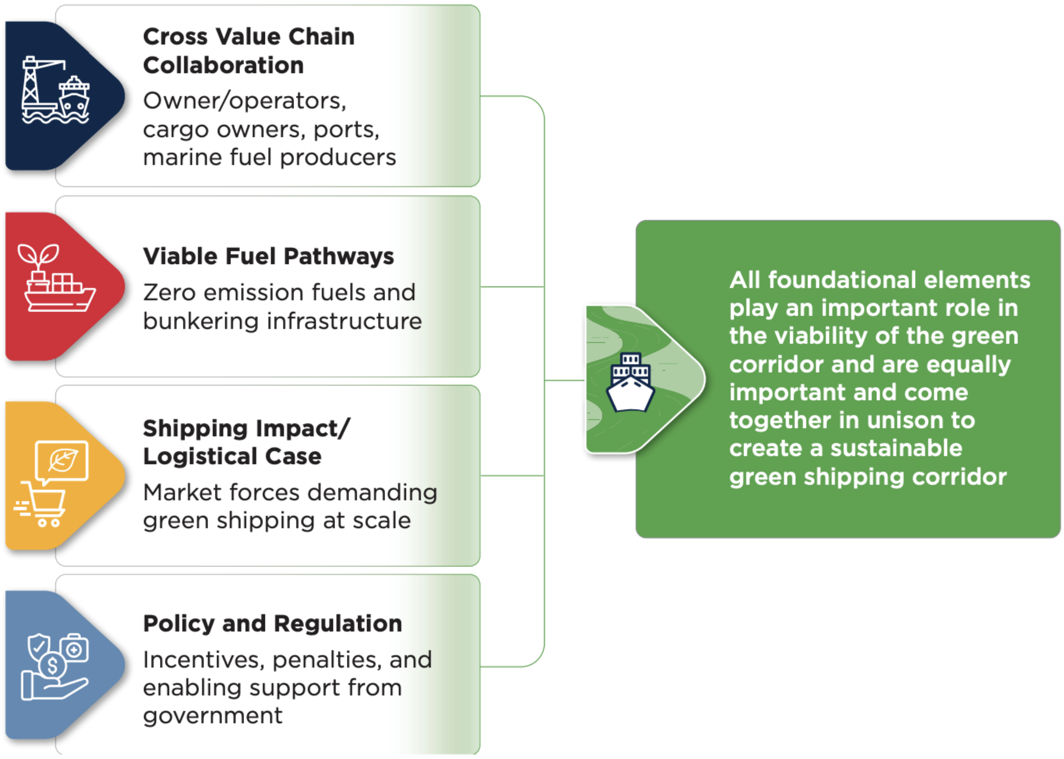


Figure 2.5: The enabling environment for Green Shipping Corridors (American Bureau of Shipping 2022).

2.5.1 Cross Value Chain collaboration

Fundamentally, a green corridor is considered a decarbonization initiative across a value chain where stakeholders are brought together to solve the same problem (American Bureau of Shipping 2022). Collaboration between each value chain member will be vital, especially in the intersection between their operational boundaries. Interaction between value chain members can improve compatibility and result in boundaries vanishing. Over time, the corridor will operate as one unit emphasizing decarbonization and economic opportunities that previously would not have been anticipated. Cross-value chain collaboration must be developed based on open communication, discussions, and robust contracts between all stakeholders.

Vessel owners and operators must make tremendous capital expenditure (CAPEX) investments by participating in green corridors. Such investments could eventually change their whole fleet composition. Owners applying decarbonization measures in their businesses are ideally positioned to participate in a green corridor effort. Factors such as fleet utilization, nearby corridors, alternative fuel bunkering infrastructure, operational optimization, and future demand for an upgraded fleet will influence how vessel owners develop their fleets. At the same time, some vessel owners are better positioned to become a part of the transition. A vessel owner with a high average fleet age might find investing in new vessels capable of operating on green corridors more attractive than a vessel owner with a new fleet. Therefore, the average fleet age and utilization are critical metrics. Shipowners must also evaluate the total cost of ownership (TCO) and address changes in cost assumptions, such as expenses associated with investing in new vessels with new technologies, operating with other fuels, and the cost of alternative fuel logistics. The next step should be to understand the emission reduction potential for each option in alignment with the total cost of ownership. The target should be selecting the option that provides the most significant GHG reduction potential per dollar spent. By analyzing such data, vessel owners can make strategic decisions regarding new builds and existing vessels' retrofits. Shipowners can also utilize the available data points to plan and decide on a scrapping schedule, thereby obtaining potential sustainable financial terms while investing in newbuilds.

A collaborative relationship between vessel owners, operators, and cargo owners is essential. As cargo owners consistently seek to mitigate their scope three emissions, indirect emissions not produced by the cargo owner, expectations with vessel owners and operators will need to be managed. Such management is usually centered around revising freight contract terms to commit to emission reduction over a longer timeline. Vessel owners and operators need to provide predictability to cargo owners to establish a lean transition and mitigate the risk of not meeting cargo owner requirements on emission reduction. Cargo owners are usually closest to the end consumer. Assessing end consumers' willingness to pay for low or zero-emission transport is essential. Such assessment can be done through the cargo's flexibility of demand. The demand can be measured through market research reports or historical shipping service sales data. Additionally, cargo owners will need to address aspects such as shipping cost to the retail value of the cargo, the contribution of shipping emissions to the total emission accounting, and the opportunities for emission reduction by choosing other transport methods. Such analysis will contribute to a better understanding the cargo's ability to carry a higher price for greener transportation.

Vessel operators will also need to communicate and collaborate with the ports constantly. As part of the development phase, vessel operators and ports will be required to discuss compatibility and safety requirements for implementing new potential solutions. Such solutions include bunkering arrangements for alternative fuels, shore power, or CCS infrastructure. Other collaborators are also highly involved in the planning process. However, ports and vessel operators are the stakeholders executing the procedures. As a result, the discussion and communication between them will be centered on operational safety and success compared to other comprehensive discussions on developing a corridor.

The development of green corridors will require ports to access alternative fuels. To do so, logistics for production, storage, and bunkering will need to be present. Ports and fuel producers must unite to reveal the green corridor's demand and bunkering profile. A profile can eventually be based on parameters such as voyages, fuel characteristics, and vessel type. Storage requirements based on the volume and physical state of the fuels will be an important area of focus. Moreover, mapping the current and expected bunkering and storage ports and their infrastructure capacity will be necessary. A thorough understanding of the regulatory requirements for handling alternative fuels, allowing processes, and safety standards should also be emphasized. By addressing these aspects, ports and fuel producers will gain a thorough understanding of the challenges and requirements they must address when deciding on a corridor.

2.5.2 Viable fuel pathways

There are multiple ways to decarbonize the shipping industry; whether it is improving vessel design, energy efficiency, or propulsion, we cannot do without implementing zero-emission fuels. As the global economy decarbonizes, the maritime industry must analyze the availability of low-and zero-carbon fuels. Green corridor agreements will benefit fuel producers by ensuring long-term demand, allowing capacity development, and securing supply.

Navigating the different fuel alternatives will require an in-depth analysis of the fuel availability. Such analysis should include a gap between the expected demand for a specific green corridor and the available supply to reveal the most critical requirements. Over a more extended period, production capacity will need to see the light, focusing on already announced projects, market estimates of alternative fuel capacity, and policy incentives for supply growth. Scaling the supply of one specific alternative fuel variant is a challenging task. However, managing the availability across several regions might further infuriate the problem. A green corridor will stimulate growth and provide a push to the demand side, helping with both fuel production pathways and port infrastructure.

A viable fuel pathway may also see the entrance of significant distinctions in the price of alternative fuels. Such differences may arise due to regional supply and policy incentives. For instance, a country such as Australia will be more capable of producing hydrogen than other countries due to its large-scale alternative energy production. The availability of alternative energy will relieve some of the price challenges related to alternative fuels. Maritime transportation will, however, have to compete with other industries regarding the demand for alternative energy. This is especially true for biofuels. Fuel cost will be an operational parameter changing over time in correlation with the deployment. A fuel cost trajectory is currently not specified among the current fuel options. Green corridors should therefore diversify the risk to allow for a multi-pathway approach.

The industry is currently considering several different fuel pathways for zero-emission vessels. However, uncertainty is flowing at a global level. Biomass-based fuels are a possible option for vessels to date. At the same time, questions such as long-term scaling potential and supply constraints have seen the light. In principle, biomass-based fuels can be used as a transition fuel in shipping; at the same time, this type of fuel will likely not be a scalable solution for the industry in the long term (Energy Transitions Commision 2021). As a result, four other fuel pathways are beeing considered. It includes green ammonia, methanol, hydrogen, and synthetic diesel. A further discussion on alternative fuel pathways is discussed in Chapter 3.

2.5.3 Customer demand, shipping impact, and logistical case

The third building block covers customer demand, shipping impact, and a logistical case. Green shipping services have seen increasing growth in recent years. As previously mentioned, more and more cargo owners now want to reduce their scope 3 emissions as they either take environmental responsibility or are required to take actions from stakeholders such as, e.g. financial institutions. There is also an increase in charterers seeking to decarbonize their operations and end customers looking to buy products with a low carbon footprint. Numerous decarbonization initiatives and collaborations between cargo owners, freight forwarders, and vessel operators have emerged recently. However, there will need to be more incentives to succeed. To accelerate decarbonization in sectors such as bulk, container, general cargo, and product tank, the demand from customers for zero-emission shipping will need to be activated and accumulated. Hopefully, this will turn individual initiatives into commercial-scale actions that can advance the industry's transition.

Customer demand and demand for emission reduction will also be critical drivers for establishing a trustworthy and reliable business case. Such a case is a critical success factor for green corridors. Establishing a solid business case will take green corridors from a theoretically possible action into a commercially practical solution. A prosperous corridor includes several links that need to be individually successful. However, if one part of the corridor fails, the whole value chain might be at risk. A robust business model should therefore strive to prevent weak links in the value chain across the corridor while at the same time developing a risk mitigation strategy for each part of the corridor. An example of such a risk mitigation strategy can be implementing multiple fuel producers instead of only one. A worst-case scenario for green corridors will include low customer demand, low price tolerance, and low margins. In such a scenario, green corridors may not be commercially viable, and an external catalyst to drive growth will be necessary.

2.5.4 Policy and regulation

Policy and regulations are vital if green corridors are to succeed. Global shipping is, by nature, geographically spread across the globe. As a consequence, governance of the global shipping industry is primarily the domain of international regulations and policies set by IMO (Global Maritime Forum et al. 2021). Regarding decarbonization, IMO has established an ambition of at least a 40% reduction in emissions from all vessels by 2030, pursuing efforts towards 70% by 2050, with 2008 as the reference year (MEPC 2021). However, these ambitions are not in line with a net-zero strategy resulting in that there have been calls from the industry for the IMO to set more ambitious reduction goals (Hobley et al. 2021). In addition, it has been called for some form of carbon taxation or levy on the shipping industry to accelerate the decarbonization process.

Such a measure is likely the most effective for industry decarbonization. At the same time, it will cause significant uncertainty regarding their prospects. First movers on zero-emission shipping will be the ones who have to manage this uncertainty. IMO will set targets and ambitions for the industry and pave the way for future fuel pathways as they can approve global fuel standards and safety regulations.

Policy and regulations will be catalysts for enabling green corridor initiatives that cover multiple stakeholders across different sectors. Green corridors might seem like a maritime-oriented incentive at first. However, the concept can potentially impact multiple sectors of the economy beyond maritime boundaries. A supportive top-down regulatory and policy environment is, therefore, vital.

2.6 Barriers to overcome

The ability to overcome barriers will be critical for developing green shipping corridors. Barriers exist on both global and corridor-specific levels forcing stakeholders to collaborate. As previously discussed, the uptake of zero-emission fuels has been acknowledged as one of the critical fundamentals for green corridors. However, it is also considered one of the most challenging barriers. It is a complex undertaking because several zero-emission fuels have a low energy density and require multiple capital-intensive installations, both onboard ships and onshore, with varying degrees of maturity. Feedstock availability, lack of production capacity, and infrastructure are all causing roadblocks, allowing for slow progress. The cost of alternative fuels will also be higher than conventional ones, making them non-competitive. Fuel prices are often related to the energy required for production versus how much energy we get from the fuel after production. Zero-emission fuels will also introduce new safety problems based on the physical features of the fuels. Toxicity, flammability, and explosiveness are all properties that will necessitate new safety precautions.

A single green corridor will introduce new perspectives of concern in addition to the uptake of zero-emission fuels. In such cases, the number of barriers will be determined by corridor-specific factors like the number of stakeholders engaged and their willingness to cooperate, sailing distance, number of ports and their locations, vessel traffic, vessel types, and the composition and maturity of the system's private and public actors. Every corridor will require a thorough identification of barriers. The barriers must be resolved through mutual commitments, agreements, collaborations, and risk sharing, and it is the stakeholder's responsibility to identify, address, and resolve them. An in-depth analysis of all barriers associated with green corridors will be a time-consuming task outside the scope of this thesis. However, this thesis highlights two critical barriers.

2.6.1 Coordinated action between stakeholders

Every stakeholder involved in a green corridor must have a reason to participate, i.e., a business case. Understanding each stakeholder's business case can be achieved by establishing a sufficient cross-value-chain team built on trust. Stakeholders involved in green corridors, such as those described in Chapter 2.3, will all have different perspectives of concern. Table 2.1 further describes and summarises some of these concerns.

Table 2.1: Critical perspectives to consider for key stakeholders in green corridors.

Stakeholoder	Perspectives of concern
Shipowner	- Technical and economic feasibility of potential fuels and technologies? - Justify the investment?
Cargo owner	- Unit cost of transporting cargo? - Risk exposure? - Paying for green transportation in line with overall business strategy?
Fuel supplier	- Market outlook? - Business case for producing and distributing new fuels? - Feedstock availability? - Corridor supporting needed investments?
Port	- Market outlook? - Business case for supplying new fuels to dock? - Investment in infrastructure profitable? - Sufficient safety zones? - Regulatory barriers? - Policy incentives?
Regulatory institutions	- Safe implementation onshore/onboard vessels? - Can financial support be justified? - Predictability in the regulations provided?
Financial institutions	- Return on investments in green fuels, ships or infrastructure? - Risk exposure?

Using green corridors to tackle problems will necessitate strong collaboration across the entire value chain and among all stakeholders, as each stakeholder will fall short of resolving the issues independently. New efforts emphasizing stakeholder cooperation must emerge, and efforts are already taking shape. Norway's Green Shipping Programme is an excellent example of such efforts. It is a public-private partnership program that includes stakeholders from all stages of the shipping value chain. The program collaborates with businesses to tackle challenges together. It also intends to develop the world's most environmentally friendly shipping sector (Green Shipping Programme 2023). Experience from the program has revealed four critical pillars for effective cross-value-chain collaboration (Slotvik et al. 2022).

Using green corridors to tackle problems will necessitate strong collaboration across the entire value chain and among all stakeholders, as each individual stakeholders will fall short of resolving the issues independently. New efforts emphasizing stakeholder cooperation will need to emerge and efforts are already taking shape. Norway's *Green Shipping Programme* is a great example of such efforts. It is a public-private partnership program that includes stakeholders from all stages of the shipping value chain. The program collaborates with businesses to tackle challenges together. It also intends to develop the world's most environmentally friendly shipping sector (Green Shipping Programme 2023). Experience from the program has revealed four important pillars for effective cross-value-chain collaboration (Slotvik et al. 2022).

1. **Involvement** - Engage and involve stakeholders and decisions makers in the green shipping corridor ecosystem. Preferably on a board or CEO level.
2. **Sharing knowledge** - Building a shared understanding and knowledge of the transport system through a multidisciplinary focus.
3. **Transparency and openness**- Building trust among the stakeholders as barriers often occur between stakeholders.
4. **A propper coordinator** - An institution or organization such as the Green Shipping Program should ensure good collaboration and keep track of development.

It is reasonable to assume that these pillars can be utilized in developing green shipping corridors. At the same time, it is critical to emphasize that no recipe fits all and that local variations and peculiarities will arise.

2.6.2 Closing the cost gap between conventional and alternative fuels

Controlling the cost gap between fossil and zero-emission fuels will be vital for achieving green corridors. Fuel accounts for about 20-35% of TCO, with practically all of the shipping industry's fuel usage being fossil-based (Mærsk Mc-Kinney Møller 2021). Fossil fuels are among the cheapest refined crude oil products. In contrast, alternative fuels have production costs that range from two to eight times that of fossil fuels. Furthermore, fossil fuels are well-established and competitive resulting in global logistics and infrastructure supporting them. In contrast, support for alternative fuels is almost non-existent. Closing the cost gap between conventional and alternative fuels will be a crucial barrier to overcome for the viability of green corridors and zero-emission shipping.

Several measures for closing the cost gap are already under investigation. As an example, the EU has put forward a proposal to implement shipping into its European Trading System (ETS), A "cap and trade" scheme where a limit is set on the right to emit specified pollutants over an area, and businesses can trade emission rights within that area (Environmental Protection Agency 2023). However, these efforts are unlikely to be adequate to achieve price parity with conventional fuel, resulting in greater demand for cost and risk-sharing systems. The Contract for Difference (CFD) mechanism exemplifies such a system. A CFD mitigates the market risks faced by suppliers of a new high-cost product by paying the supplier the difference between a predetermined reference price reflecting the old technology, which in this case is the cost of conventional fuel, and a strike price set at a value required for the new technology to be viable (Pandey et al. 2022). Figure 2.6 illustrates the components of a zero-emission shipping investment decision under a CFD program.

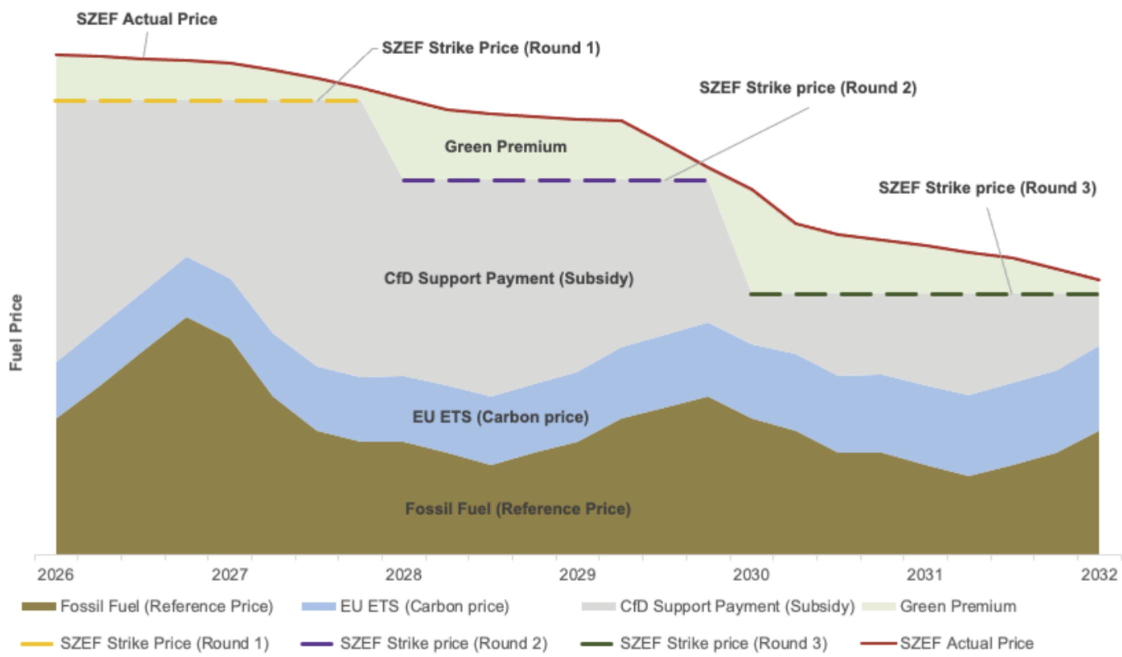


Figure 2.6: Fuel-only contract for difference mechanism (Pandey et al. 2022).

A shipping-specific CFD model will focus on fuel costs, with ship operators receiving direct government subsidies for the cost difference between the strike price and fossil fuels. As a result, vessel operators will contract with fuel producers based on this fixed strike price. A fixed strike price means fixed revenues. As a result, regardless of market conditions, fuel producers will be forced to reduce costs to boost profits. This strategy, hopefully, will accelerate a cycle in which optimization drives down fuel prices, cutting the cost of the shipping industry's energy transition once more (Pandey et al. 2022).

Chapter 3

Fuel pathways and energy replenishment strategies

Over the past decades, Heavy Fuel Oil (HFO) has been the dominant fuel alternative for newbuilds. This is due primarily to its low cost, high availability, and high energy density. At the same time, such fuels will generate large amounts of local and global emissions. Zero-emission vessels operating in green corridors will be challenging to achieve without investigating alternative fuel pathways. Such admissions will reveal a wide range of options while also producing a significant amount of uncertainty. Some of the uncertainty can be related to the production and distribution of the fuels. Additionally, several alternative fuels demonstrate lower volumetric density than conventional fuels, creating additional challenges regarding occupied volume onboard the vessels. Therefore, energy replenishment strategies shall also be emphasized as an area of research as they may be a solution to the issue. With these considerations in mind, navigating the different fuel pathways will be critical for the shipping industry's zero-emission goal and the developing of green shipping corridors.

The following chapter gives an overview of alternative fuel families, energy converters, and energy carriers that can assist shipping in achieving zero-emission status. Relevant fuel families are discussed, followed by relevant energy converters and carriers. The chapter also outlines potential fuel paths and alternative replenishment strategies and acts as a knowledge base for future fuel mapping vessels operating in green corridors.

3.1 Fuel families

Fuels can originate from various energy sources, resulting in considerable differences in life cycle emissions and cost. The primary energy source and the production strategy are often used to determine how to define a green fuel. Based on the principal energy source of the fuel, marine fuels can be segregated and classified into "fuel families." In maritime transportation, four fuel families are present and cover four different categories:

1. **Fosil fuels** - Substances containing hydrocarbons like coal, oil, natural gas, oil shale, and tar sands. They are found in the earth's crust and are exploited as an energy source by combustion.
2. **Biofuels** - Fuels produced over a short timespan from biomass.
3. **Electrofuels (e-fuels)** - Developed from using captured carbon dioxide, carbon monoxide, and hydrogen from renewable electricity.
4. **Blue fuels** - Fuels developed using natural gas and Carbon Capture and Storage (CCS) technology.

Traditional fuels will face competition from blue fuels, e-fuels, and biofuel. At the same time, utilizing such fuels will require a more sustainable production strategy. It involves using renewable energy and less water and implementing a safe and efficient CCS process.

3.1.1 Fossil fuels

Fossil fuels are generated from hydrocarbon-containing material subjected to high pressure in the earth's crust for thousands of years, typically dead plants and animals. This substance is extracted, processed, and burned as fuel. Coal, crude oil, and natural gas are the primary high-carbon resources exploited through mining and drilling operations. Fossil fuels are utilized to power marine engines in the marine environment.

For many years, fossil fuels have dominated as a worldwide energy source. The most common in maritime transportation is HFO and Marine Gasoil (MGO), which have been crucial for the accessibility and dependability of global fuel supplies. Simultaneously, such fuels have had, and continue to have, a significant environmental impact. As fossil fuels generate considerable volumes of CO_2, they contribute significantly to global GHG emissions and air pollution.

3.1.2 Biofuels

Biofuels, as opposed to fossil fuels, are derived from biomass, such as wood and wood crops, agricultural waste, waste from industry, farms, and households. Such fuels are generally easy to process and transform into energy-dense hydrocarbon fuels. The industry considers several biofuels for usage in ships. Hydro-treated vegetable oil (HVO), fatty acid methylester (FAME), as well as liquefied biogas (LBG) are the most emphasized fuels. Other alternatives are also available (DNV-GL 2019a).

Biofuels can be a solution for GHG reduction even though such fuels do not directly reduce CO_2 emissions. As for the combustion of fossil fuels, biofuels add CO_2 to the atmosphere. However, CO_2 emitted from the combustion of biofuels can be considered a part of a natural cycle where the same amount of emitted CO2 is captured from the atmosphere by the feedstock plants as they grow. As a result, we consider biofuels as carbon-neutral. Figure 3.1 illustrates a simple biofuel cycle.

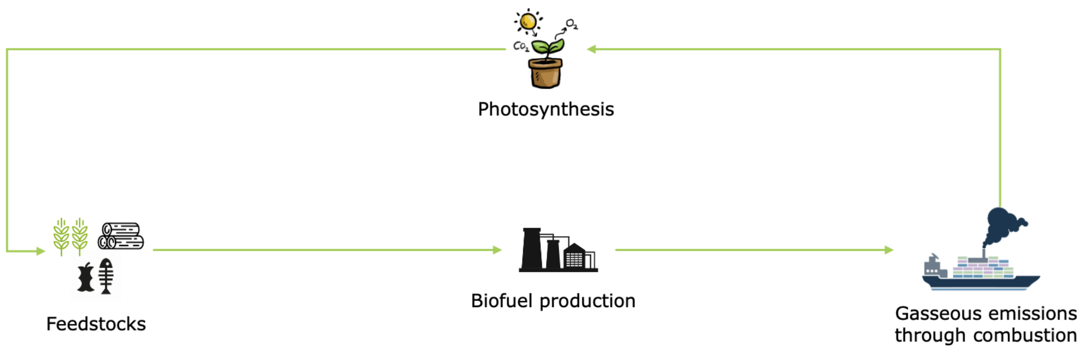


Figure 3.1: Simple illustration of a biofuel cycle.

The use of biofuels in maritime transportation is very limited to date. The future use of biofuels will rely on the availability of sustainable biomass. Simultaneously, the availability of sustainable biomass must be seen in conjunction with other industries where biomass and energy-dense hydrocarbons are needed. Aviation is an example of such an industry where biofuels are considered an alternative, as electrification of long-distance flights will be challenging. In a scenario where the availability of sustainable biomass is low, biofuels are expected not to be competitive with options such as electrofuels and blue fuels (DNV 2022).

3.1.3 Electrofuels (e-fuels)

Electrofuels, also known as green fuels, are produced using electrolysis with hydrogen as a key ingredient. E-fuel production necessitates using two key components: Water and electricity. Through electrolysis, water is split into hydrogen and oxygen using electricity. Hydrogen is critical since it can be used in synthesis processes alone or combined with other substances, such as nitrogen and carbon dioxide. Depending on the fuel produced, different catalysts are employed. Using electricity and electrolysis allows for producing fuels such as e-MGO, e-LNG, e-methanol, e-ammonia, and hydrogen. These fuels are drop-in fuels because they require minimal engine and fuel systems modification to replace or blend in with standard fuel combustion engines (DNV-GL 2019b).

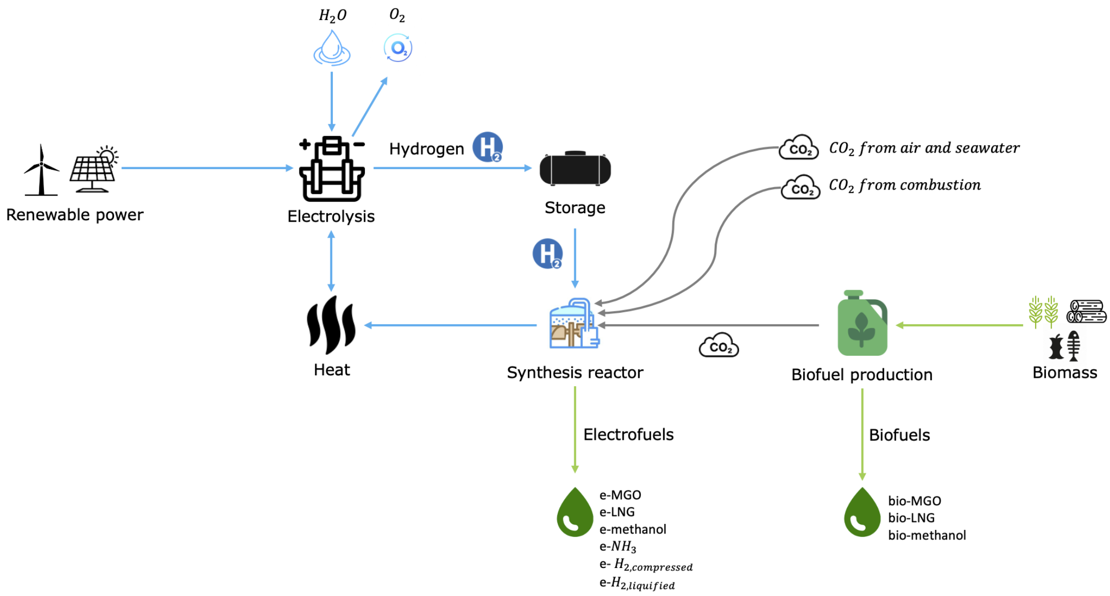


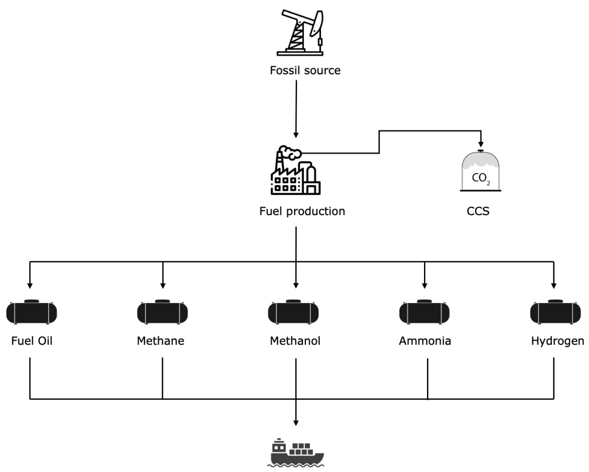
Figure 3.2: Process steps in the production of electrofuels (developed from Taljegard et al. 2015).

Electrofuels and their availability will highly rely on the availability of renewable electricity. The success factor for such fuels will see the need to decrease fossil energy for electricity generation. At the same time, the fluctuating nature of renewable electricity production, specifically those generated from wind, can generate challenges. Moreover, solar energy production calls for a large-scale production capacity to ensure sufficient supply to networks highly dependent on these renewable sources. At the same time, addressing that these renewable energy systems might lack supply capability in periods of high energy demand and low wind and sun irradiation conditions is vital. To handle the supply-and-demand distinction, a substantial energy storage capacity is critical(DNV-GL 2019a).

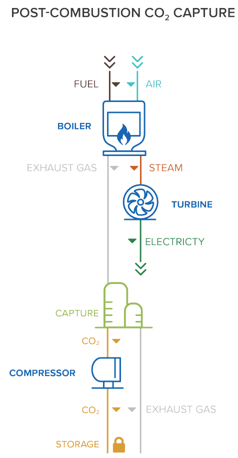
3.1.4 Blue fuels & CCS

Blue fuels are utilizing fossil sources in combination with CCS technology to meet the demand for zero-emission fuels. CCS onboard ships are considered an additional measure to reduce CO_2 emissions. However, the industry emphasizes such technology as one of the most crucial to reducing GHG emissions. CCS technology is based on capturing the CO_2 and transporting it to areas where it can not cause damage, such as below the seabed. Norway is among several countries starting to invest in CCS technology. Norway aims to create a full-scale CCS project through the Longship project, demonstrating the ability to capture CO_2 from industrial plants, transport it, and store it safely beneath the seabed (Ministry of Petroleum and Energy 2021). Until now, CCS projects have been centered around large-scale emission sources such as factories, waste management facilities, and power generation plants. However, as the maritime industry is heavily addressing the need for decarbonization, new use areas will arise, such as utilizing CCS in producing marine fuels and post-combustion capture onboard vessels.

The availability and success of blue fuels will highly rely on the effectiveness of carbon capture. In addition, infrastructure for permanent storage must be present. At the same time, mature CCS technology, in combination with sufficient infrastructure, could make CCS onboard vessels a viable alternative where fossil fuels can continue to be used (DNV 2022). The most common onboard CCS strategy is the concept of post-combustion capture of CO_2, and such a process is illustrated in Figure 3.3b. Nevertheless, such technology is considered immature to date. The low maturity of onboard CCS and the low availability of support infrastructure need to be addressed and further developed. Despite several challenges, embedded CCS systems might play an essential role in meeting emission targets before carbon-free fuels become viable due to the high maturity of onshore applications.



(a) Blue fuels production chain.



(b) Post-combustion CCS onboard vessels (Global CCS institute 2023).

Figure 3.3: Blue fuel production and CCS strategies for maritime applications.

3.2 Energy Converters

Energy converters are critical components that must be present onboard ships to enable power. Marine powering systems are examples of such converters that enable converting the fuel's energy into useful thrust to match the ship resistance at the required speed (Molland et al. 2014). Several energy converter options are available for ship propulsion. Conventional fuel-consuming converters such as Internal Combustion Engine (ICE) and gas and steam turbines are standard options in vessel design. At the same time, energy converters such as fuel cells and nuclear-powered systems are under development and can potentially influence the future energy converter mix. In addition, alternative no-fuel-consuming energy converters such as wind-assisted and battery-electric systems are possible solutions for energy conversion. The following chapter will focus on five critical energy converters, including ICEs, fuel cells, gas turbines, batteries, and hybrid systems.

3.2.1 Internal combustion engines

ICEs are a mature technology used in automotive, off-road, and maritime industries for over 100 years. The technology comprises heat engines in which fuel combustion happens by employing an oxidizer, generally air, in a combustion chamber. In maritime applications, ICEs are used for propulsion and power generation. The fuel injects at a controlled high pressure in a marine ICE. A mixture of fuel and air is then compressed inside the engine cylinder through a piston, resulting in an explosion of the mixture due to compression. Such a mechanism results in the release of heat, which increases the pressure of the burning gas. The increase in pressure pushes the piston downwards and transmits the transverse motion into a rotational motion of the crankshaft using connecting rod arrangements (Raunek 2019). Such procedures are then repeated continuously to maintain the power output depending on the type of engine and its usage. Furthermore, the crankshaft connects through a flywheel to either an alternator or a propeller arrangement. Explosions in the ICE must be repeated continuously to obtain continuous crankshaft rotation. Figure 3.4 illustrates the principle mechanisms in a marine ICE.

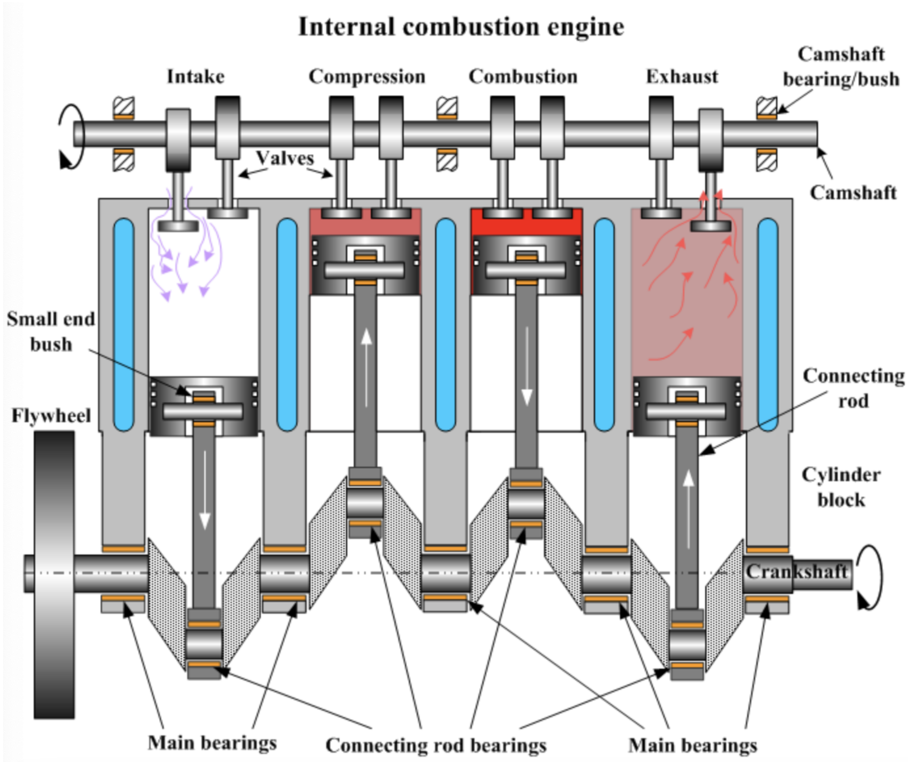


Figure 3.4: Principle mechanism of an ICE (SubsTech 2021).

Marine engines usually divide into three categories; slow-, medium, and high-speed. Slow-speed engines are a two-stroke configuration operating at around 80-140 RPM with a maximum limit of 300 RPM. Such engines are commonly used for propulsion in large vessels. Medium-speed engines operate within a range of 300-900 RPM. They are typically four-stroke engines and can both be used for propulsion and auxiliary power generation on board various vessel types. High-speed engines are four-stroke engines operating at speeds above 900 RPM. As for medium-speed engines, high-speed are used for propulsion and auxiliary power. However, high-speed engines are more common in smaller, high-speed vessels (DNV-GL 2019b). Most of the commercial shipping fleet utilizes ICEs. The entrance of dual fuel and pure gas ICEs has resulted in propulsion and auxiliary power supply to vessels of different sizes and operational profiles. At the same time, ICEs is expected to continue to be a key energy converter for low- and zero-emission fuels such as ammonia and hydrogen.

3.2.2 Fuel cells

A fuel cell is an electrochemical energy converter that converts the chemical energy of a fuel, often hydrogen, and an oxidizing agent, such as oxygen, into electricity. Fuel cells differ from batteries because they require constant oxygen and fuel to sustain the chemical reaction. Chemical energy in batteries derives from existing chemicals, and such energy sources will eventually disappear. On the other hand, fuel cells may produce power for as long as fuel and oxygen are available (Winter and Brodd 2004).

Fuel cells come in many different configurations. However, the principle function and mechanism is the same. Three main components are present, an anode, a cathode, and an electrolyte. Through chemical reactions at the interface of the components, fuel is consumed, and an electric current is created, which can be utilized to power devices such as propulsion systems. The fuel, usually hydrogen, is oxidized at the anode through a catalyst. This process turns the hydrogen into a positively charged ion and a negatively charged electron. The fuel cell's electrolyte element is specifically designed so that only positive ions can pass through it. As a result, the electrons are forced to travel through a wire, creating an electrical circuit. When the ions arrive at the cathode, they are reunited with the electrons, and the two react with a third substance, usually oxygen, to create water. The functional principle of a fuel cell is further illustrated in Figure 3.5.

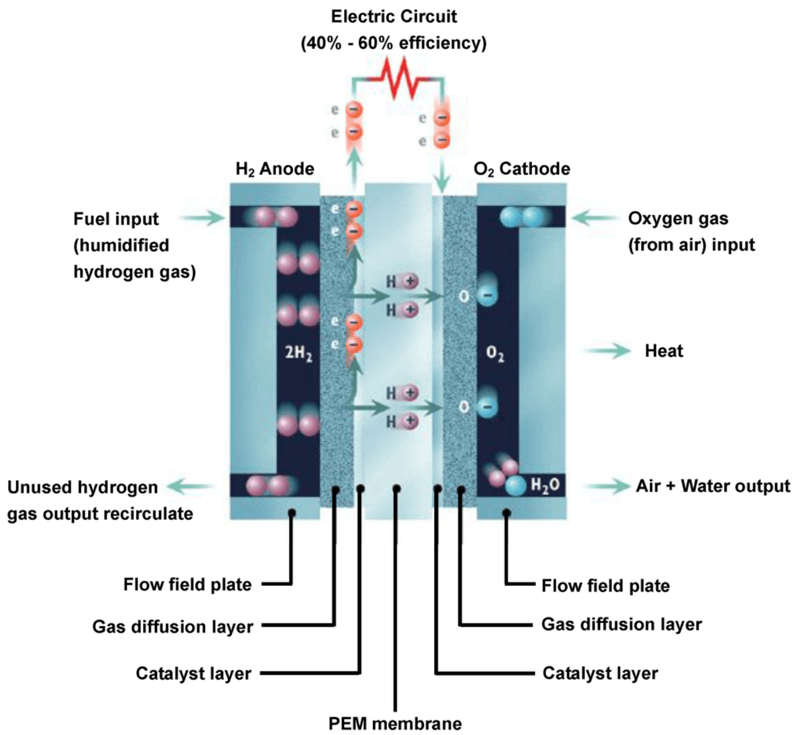


Figure 3.5: Principle mechanism of a fuel cell (Spiegel 2021).

Fuel cells have several advantages compared to other energy converters. It can decrease pollution of toxic GHG substances such as CO_2, Nitrogen Oxide (NO_x), and Sulphur Oxide (SO_x). Simultaniously, the electrical efficiency can outperform marine diesel generators depending on the fuel cell configuration. The electrical efficiency of a fuel cell can further be increased by connecting heat recovery systems. Fuel cells also cause insignificant noise and vibration and expect less maintenance than conventional combustion engines and turbines. However, lifetime, durability, costs, and regulatory uncertainties are issues calling for more research and development to make fuel cell energy converters even more competitive (DNV-GL 2019b).

3.2.3 Gas turbines

Gas turbines are one of the most commonly used energy converter technologies for power generation. Such turbines are considered a type of ICE in which an air-fuel mixture burns hot gases that spin a turbine to produce power (Wärtsila 2023). A gas turbine consists of three main components mounted on the same shaft, a compressor, a combustion chamber, and a turbine. The compressor can either be configured as axial flow or centrifugal flow. However, axial flow compressors are more common for power generation due to their high flow rates and efficiencies. An axial flow compressor consists of several levels of stationary rotating blades where the air is transported parallel to the axis of rotation and increasingly compressed through each stage. Such a process reduces the volume of the air while at the same time increasing the temperature (Wärtsila 2023). A smooth acceleration must be performed to reach a firing speed, i.e., the required speed before fuel adds to the system and ignition can occur. Turbine speed may vary depending on the design and manufacturer. However, operational speeds usually range from 2000 to 10000 RPM. Gas turbines can operate on various fuels, including natural gas, synthetic fuels, and fuel oils. In contrast to ICEs, where combustion happens intermittently, the combustion in a gas turbine occurs continuously. Figure 3.6 illustrate the working principle of a gas turbine.

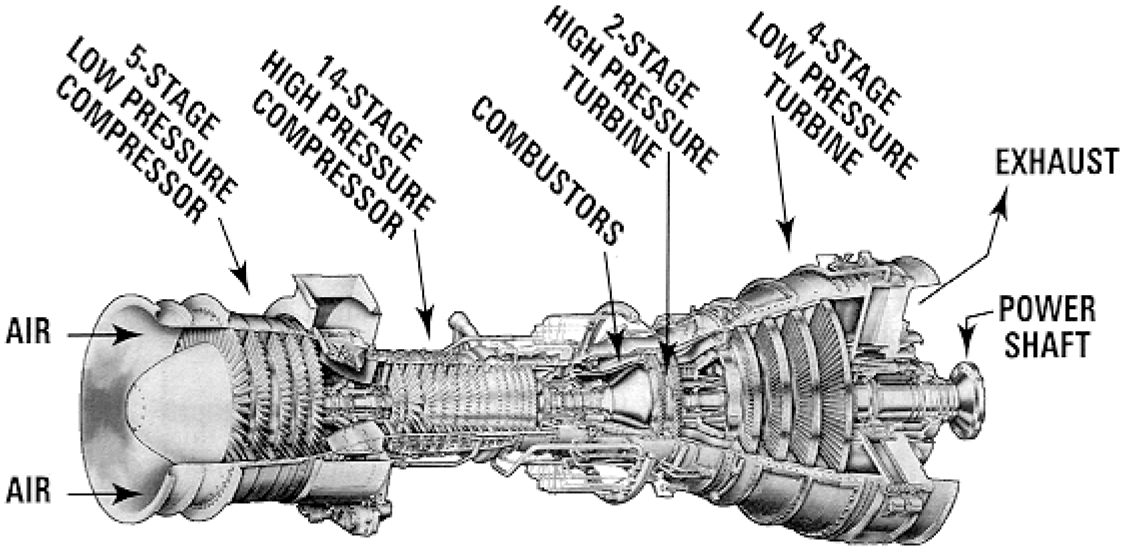


Figure 3.6: Working principle of a gas turbine (Leduc 2021).

Gas turbines have been utilized to propel vessels for over 40 years. However, they usually target niche markets such as naval ships and pleasure yachts, where the benefits of gas turbines are highly valued. Gas turbine producers see new opportunities for the energy converter due to the greater use of Liquid Natural Gas (LNG) within the industry, efficient and clean burning process, increased concerns regarding GHG emissions, and the need for fuel flexibility. LNG powered large container vessels and retrofitting of existing LNG carriers are currently the two most promising market segments for the use of gas turbines (Riviera 2020).

3.2.4 Batteries

Batteries are energy converters, converting chemical energy directly to electrical energy. A central characteristic of batteries is that the stored energy will, at some point, run out, resulting in a dead battery unable to provide electrical energy, and recharge is required. Several types of batteries exist to date. However, some variants have been more favorable than others. Lithium-ion batteries have, for instance, seen a take-off in shipping over the last few years due to a massive price drop. It can be seen in parallel with the developments in the automotive industry, which have driven the technology and scale of production (Mjøs 2019). Battery systems used for marine applications differ from those used in the automotive industry, requiring a different battery management system, higher power, energy delivery, and greater longevity. Despite the differences in battery systems, the battery cells are more or less the same resulting in the maritime industry benefiting from this trend.

Batteries in marine applications have several benefits. They are among the few options for making vessels operate with zero emissions. Batteries are especially suitable for vessels sailing shorter distances, e.g., ferry routes. A fully electric vessel supplied with electricity from zero-carbon renewable sources such as wind, hydropower, and photovoltaic will demonstrate zero GHG emissions to the air. Batteries are also enablers for the reduction of fuel consumption but also maintenance costs. In addition, the electric power will decrease noise and vibration while simultaneously welcoming vessel responsiveness and thereby safety (Mjøs 2019). Despite several benefits, some trade-offs must be made. The initial cost of batteries is usually higher than traditional energy converters, as power systems and charging infrastructure investments can be expensive. Batteries are most common in vessel segments such as Ro-Pax and passenger ferries. However, offshore vessels, fishing vessels, cruise ships, and tug boats are starting to utilize the technology. Deep-sea shipping is also starting to implement batteries to optimize power management in propulsion and auxiliary power use to save fuel and maintenance costs.

3.2.5 Hybrid systems

Hybrid systems combine combustion engines with battery power to optimize engine operation while at the same time reducing emissions. Such energy converter systems are specially tailored for vessels with flexible operation profiles, running hours, and power demands (MAN Energy Solutions n.d.). Marine hybrid systems usually consist of one or more main engines, often a combustion engine, GenSets, switchboard, converters, electric motors, energy storage systems, gearbox, and propeller. Figure 3.7 presents an illustrative overview of a typical marine hybrid system.

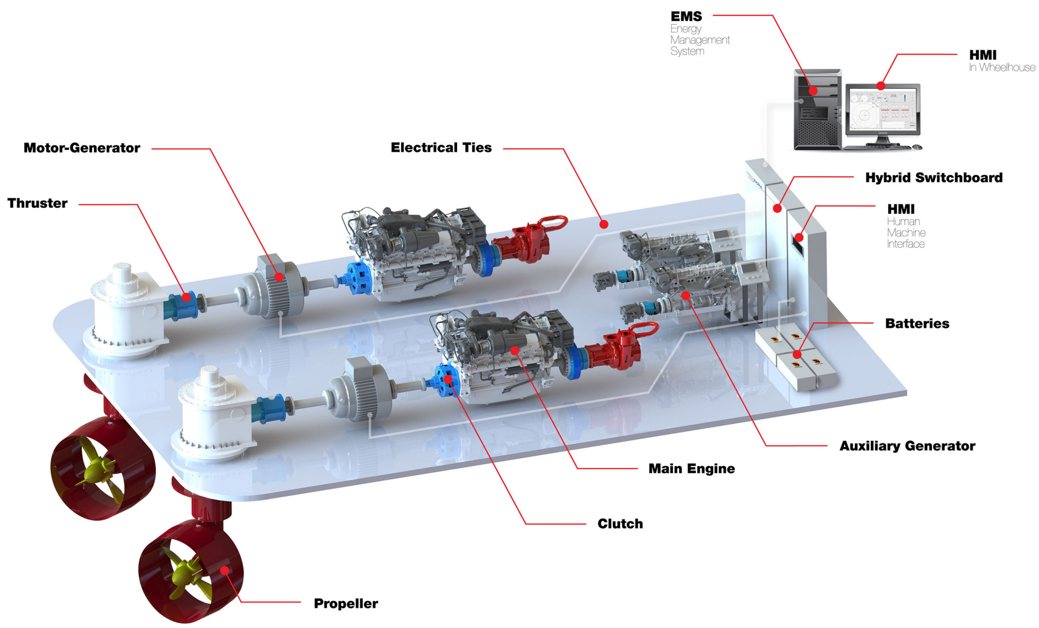


Figure 3.7: Example of a marine hybrid system (AKA Energy Systems 2023).

Marine hybrid systems will imply numerous advantages. Despite lowering emissions and fuel consumption, hybrid systems reduce generator wear and tear, maintenance costs, and downtime. Such systems also provide smoother power delivery and avoid transient loads on main engines. It should also be highlighted that marine hybrid systems can benefit several vessel types. Offshore vessels can, for instance, benefit from increased power delivery, redundancy, and safety, while vessel segments such as cruise and pleasure yachts can benefit from low noise and vibrations.

3.3 Energy Carriers

Energy carriers are a common term for electricity, heat, solid, liquid, and gaseous fuels. Shipping is an industry utilizing several different fuels. Some fuels are more common than others, resulting in no clear winner or preferred option in the maritime fuel market. However, the industry focuses on alternative fuels with low or zero emissions. For green shipping corridors, the entrance of alternative fuels will be vital for the concept's success. It has to be present in the port or along strategic points on the corridor route. The following chapter will provide an overview of a selection of fuel alternatives and pathways optional for the industry to emphasize. The focus will be on general properties, technology, infrastructure, environmental impact, and scalability.

3.3.1 Conventional fuels (HFO, MGO, LSFO and VLSFO)

HFOand MGO are the most dominant energy carriers in maritime transportation. These fuels have been used for decades, causing significant GHG emissions. Alternatives to HFO and MGO are Low Sulphur Fuel Oil (LSFO) and Very Low Sulphur Fuel Oil (VLSFO), options containing less sulfur and compatible with the current IMO regulations.

HFO is a variant of fuel oils with a dark brown or black viscous consistency. It is extracted from fragments from the distillation and cracking process of petroleum. As a result, HFO is attenuated with several different compounds, such as aromatics, sulfur, and nitrogen, making emissions upon combustion more polluting compared to other fuel oils (McKee et al. 2014). HFO is a preferred fuel source for propulsion, mainly due to its high availability and relatively low price compared to other cleaner fuels. However, the use, and carriage of HFO onboard vessels, come with several concerns, such as the risk of oil spills and the emission of toxic compounds and particulates. HFO are commonly used with exhaust gas treatment systems such as scrubbers to comply with current emission regulations.

MGO is a variant of marine fuels comprised entirely of distillates, i.e., all components of crude oil that evaporate in fractional distillation and condense from the gas phase into liquid fractions (Oiltanking 2023). MGO is usually a combination of different distillates similar to diesel fuel but with a higher density. Unlike HFO, MGO does not need to be heated during storage. MGO is also considered a low-sulfur fuel oil, with a sulfur content between 0,10 and 1,50 m/m % (Wankhede 2020).

3.3.2 LNG

LNG is a hydrocarbon fuel predominantly consisting of methane and some ethane. It is considered the fuel with the most negligible content of hydrocarbons and, therefore, the highest potential to reduce GHG emissions (DNV-GL 2019b). It is a colorless, non-toxic, non-corrosive fuel, free of smell with high flammability. Furthermore, methane is a potent and highly flammable GHG. Careful methane slip control will therefore be necessary when using the fuel.

Energy converters capable of utilizing LNG as ship fuel are ready and available. ICEs are the most common energy converter with 2-stroke and 4-stroke configurations available. Fuel cells as an energy converter for LNG are also feasible but are rare in the industry. The energy density of LNG is approximately 18 percent higher compared to HFO. However, the volumetric density (kg/m^3) is only 43 percent of HFO (DNV-GL 2019b). The volumetric properties of the energy carrier also imply that LNG will require significantly more storage space than conventional fuels. Cylindrical LNG tanks usually occupy over three times the volume of a conventional petroleum-based storage tank, making less space for payload.

LNG has been an available fuel alternative for several years. LNG carriers have mainly utilized it with utilization dating back to the 1950s. However, other vessel segments have recently started utilizing LNG as an energy carrier. According to DNV (2023b) Alternative Fuels Insight platform (AFI), 255 LNG-fueled vessels were in operation by the end of 2022. Despite an expected increase in LNG-powered vessels and a high volume of vessels on order, dedicated LNG bunkering infrastructure for ships still needs to be improved. However, improvements are being made across the globe. A significant amount of bunkering and distribution of LNG is still taking place by road. However, several dedicated bunkering vessels have recently been delivered for operation in critical areas, and more vessels are in the pipeline. Increasing the availability of LNG bunkering in ports will be decisive for the further use of such energy carriers.

3.3.3 LPG

Liquefied petroleum gas (LPG) is a liquid mixture of propane and butane extracted from byproducts of oil and gas. LPG can, however, be produced from renewable sources. An example of such products is LPG as a byproduct of renewable diesel production (DNV-GL 2019b). Propane has a boiling point of -42 degrees and is found in the gas form under ambient conditions. Liquid propane can be obtained by adding moderate pressure, specifically 8, 4 bar at 20 degrees Celsius. Butane is standard as n-butane or iso-butane with a boiling point of -0, 5, and -12 degrees, respectively. Lower boiling points result in butane being liquefied at lower pressures than propane. LPG also has a lower volumetric density than traditional fuels, making LPG fuel tanks 2-3 times the size of traditional tanks (DNV-GL 2019a).

The combustion of LPG emits around 16 percent less CO_2 compared to HFO. The number can increase to 17 percent if the complete life cycle, including production, is considered. However, butane and propane have three times the global warming potential of CO_2. Therefore, uunburned LPG escaping into the atmosphere should be carefully considered. Nevertheless, LPG eliminates SO_x emissions and is also expected to reduce Particular Matter (PM) emissions. NO_x emissions will highly depend on the technology utilized (DNV-GL 2019a).

Three leading energy converters are optional for LPG, including two-stroke diesel cycle engines, four-stroke lean-burn Otto cycle engines, and gas turbines. Storage of LPG has to be done under pressure or refrigeration. However, LPG is only sometimes available in the ideal pressure and temperature range. For this reason, necessary equipment and installations must be carried by both the bunkering vessel and the vessel to be bunkered to ensure a safe bunkering operation. To date, pressurized and semi-refrigerated storage tanks are the preferred options for onboard storage. This is mainly due to the simplicity of bunker operations such tanks implies. LPG currently fuels 48 vessels in the global fleet. Most of the fleet consists of LPG tankers and some gas tankers (DNV 2023b).

3.3.4 Methanol

Methanol is an organic chemical, also known as the simplest alcohol, with the highest carbon and the lowest hydrogen content. It is a light, flammable, colorless liquid with a distinctive alcoholic cent similar to ethanol (CDC 2021). Methanol has many applications, including coatings, paint, plastic packaging, and building materials. At the same time, methanol is utilized as a transport fuel and a hydrogen carrier for fuel cells. It extracts from several feedstocks, including natural gas, coal, and renewable resources such as black liquor from pulp and paper mills, forest thinning, or agricultural waste (DNV-GL 2019a). Methanol can even be directly extracted from CO_2 captured from power plants.

Methanol is commonly used in two configurations of ICEs, either in a single two-stroke diesel-cycle engine or a four-stroke, lean-burn Otto-cycle engine. However, the single-two-stroke diesel engine is currently the only commercially available option. Storage-wise, methanol is a liquid fuel and can therefore be stored in standardized fuel tanks. However, due to its low flash point of 11 degrees, minor modifications are required to comply with rules currently under development at IMO. Distributing methanol to ships is currently performed through bunker vessels or trucks. It demonstrates success through specific vessels such as the Swedish Ro-Pax ferry *Stena Gemanica* operating between Gothenburg and Kiel (Bahtić 2023).

ICEs fueled on methanol can reduce CO_2 emissions by approximately 10 percent compared to traditional fuels. At the same time, the exact percentage will rely on whether methanol is compared with substances such as HFO or distillate fuel. By analyzing the whole life cycle, including production from natural gas, the total CO_2 emissions are considered equivalent or slightly higher than the corresponding emissions of oil-based fuels (DNV-GL 2019a). Methanol can, however, be characterized as a net carbon-neutral fuel by extracting the fuel from renewable feedstock sources such as biomass.

The demand for methanol has steadily increased over the past years and is expected to grow with a compound annual growth rate of 5,5% until 2027 (Nestler et al. 2018). The production capacity is currently at around 110 million tonnes. This amount's energy content is about 55 million tonnes of conventional oil. Asia is the largest consumer of methanol, accounting for around 60 percent of global demand. Regions such as Western Europe, North America, and the Middle East account for around 30 percent of global demand. With high availability globally, current methanol production is expected to safely supply the shipping sector until 2030, assuming a moderate growth rate (DNV-GL 2019a).

3.3.5 Hydrogen

Hydrogen is a chemical substance with atomic number 1. It is the lightest existing element and operates as a gas of diatomic molecules under normal conditions. Hydrogen is a non-toxic, tasteless, scentless, and colorless substance with highly combustible properties (Jolly 2022). There are several ways to store hydrogen onboard ships. Hydrogen is stored as a liquid, compressed gas, or chemical bond. With a boiling point of −253 degrees Celsius at 1 bar, it can be liquefied at temperatures up to −240 degrees by increasing the pressure to 13 bars. Liquefied hydrogen is approximately three times as energy-dense as HFO. However, the volumetric density is only around seven percent that of HFO. Such properties result in hydrogen occupying five times the volume compared to the same energy stored in HFO. By utilizing hydrogen as compressed gas, the volumetric properties become approximately 15 times the same amount of energy stored as HFO (DNV-GL 2019a). Hydrogen can be extracted from various energy sources, including fossil fuels, natural gas, oil, and coal. Production through electrolysis of renewable and reforming of natural gas are also possible strategies. In maritime transportation, hydrogen extracted from reforming natural gas is most common, capturing the resulting CO_2 from such a process could eventually accellerate a zero-emission value chain.

Several technologies are feasible for hydrogen as an energy carrier. Fuel cells are expected to play a critical role in future use. However, other alternative technologies, including hydrogen-fueled gas turbines and ICEs, are under investigation, either as stand-alone energy converters or in combination with fuel cells. Hydrogen-fueled ICEs are currently not commercially available. They are also expected to demonstrate lower efficiency than traditional ICEs, making further technological development necessary. A combination of fuel cells and batteries using peak shaving effects is expected to be the most promising solution for shipping. Proton exchange membrane fuel cells (PEMFC) are also included in the analysis due to their flexible materials that could improve fuel cell lifetime (DNV-GL 2019a).

Current hydrogen production is mainly based on existing land-based infrastructure. The demand for hydrogen as ship fuel is minimal, with only six hydrogen-fueled vessels currently operating (DNV 2023b). The public demand for hydrogen as ship fuel is low, resulting in no current distribution or bunkering infrastructure. However, technology is available, making an upscale of both distribution and bunkering feasible. Hydrogen production through electrolysis is, for instance, commercially available today. Such techniques are especially suitable for local port production if sufficient electrical energy is available. Electrolysis would also eliminate the need for a long-distance distribution infrastructure. Storage-wise, liquid hydrogen in tanks is considered a promising solution as liquid hydrogen containers, capable of storing 3000 kilograms of hydrogen, are available in the market (Decker 2019). A future scenario could be liquefied hydrogen transported to ports from storage sites that produce hydrogen from renewable energy, such as wind power. Several transportation methods are optional, including road, ship, and pipelines depending on size, volume, and distance factors.

Hydrogen can be considered a low-alternative fuel for shipping if it is generated from renewable or nuclear power sources. An alternative option is to produce hydrogen from natural gas in combination with CCS. As discussed in 3.2.2, using hydrogen in fuel cells will not produce any CO2 and can simultaneously eliminate NO_x, SO_x, and PM from ships.

3.3.6 Ammonia

Ammonia is an inorganic energy carrier consisting of nitrogen and hydrogen. It is a colorless gas with a distinct smell commonly used to produce fertilizers (IEA 2021). Due to several challenges related to the safety, regulations, storage, space, and weight of hydrogen as a ship fuel, Ammonia has gained more and more interest as an alternative energy carrier in maritime transportation. It liquefies at a higher temperature than hydrogen and is also 50% more energy dense per unit volume, making storage and distribution much easier (DNV-GL 2019b).

Two energy converters are relevant for ammonia as fuel in ships, namely fuel cells, and ICEs. Combustion of ammonia has shown increased power output compared to traditional fuels and hydrogen. At the same time, some disadvantages have been discovered. ammonia is a toxic substance with high ignition temperature, low flame speed, high heat of vaporization, and narrow flammability limits. In addition, ammonia is corrosive to plastics, copper, and nickel, making use of such metals in ICEs unfavorable (DNV-GL 2019b). Fuel cells utilizing ammonia are currently a technology too immature for commercial scalability. However, such technology expects to constitute significant potential in the long-term perspective.

Well-to-wake emissions from ammonia production are highly dependent on the production method. The energy carrier is usually divided into brown, grey, blue, and green ammonia. Brown and grey are extracted from coal and methane, while blue ammonia is produced similarly but utilizes CCS to handle CO_2 emissions. Green ammonia is produced using renewable energy in combination with electrolysis to split water, making it the most environmentally friendly production method (Magnusson and Murphy-Cannella 2021).

High demand for ammonia in land-based industries has resulted in a well-developed infrastructure for handling and transportation. The lack of such infrastructure for marine applications is, however, a reality and is considered a barrier to the success of the energy carrier. To date, ammonia is transported by multi-cargo gas carriers capable of transporting LPG, where estimates of cost and equipment are already well developed. Ammonia can benefit from the maturity of these measures by estimating transport costs and needed equipment from those of LPG (DNV-GL 2019b).

3.4 Summarizing the fuel pathways

Until now, a comprehensive review of fuel families, energy converters, and energy carriers has been presented. Combining these three elements will reveal numerous fuel pathways the shipping industry can exploit. Currently, 16 different pathways are expected to be shipping options; Table 3.1 provides an overview of the 16 fuel pathways.

Table 3.1: Optional fuel pathways for maritime transportation (Adopted from DNV-GL 2019b).

Energy carrier	Fuel family	Fuel pathway
HFO, MGO and VLSFO	Fossil fuel	Fossil - HFO,MGO,VLSFO - ICE
LNG	Fossil fuel	NG - LNG - ICE
	Fossil fuel	NG - LNG - FC
LPG	Fossil fuel	Fossil - LPG - ICE
Methanol	Fossil fuel	NG - Methanol - ICE
	Biofuel	Biomass - Methanol - ICE
Hydrogen	Fossil fuel	NG - H2 - ICE
	Fossil fuel	NG - H2 - FC
	Green fuels	Renewable - H2 - ICE
	Green fuels	Renewable - H2 - FC
Ammonia	Fossil fuels	NG - NH3 - ICE
	Fossil fuels	NG - NH3 - ICE
	Green fuels	Renewable - NH3 - ICE
	Green fuels	Renewable - NH3 - ICE
Advanced biodiesel	Biomass	Biomass - biodiesel - ICE
Electric	Electricity	Energy mix - Electricity - Battery-electric system

A thorough insight into possible fuel pathways is vital for understanding well-to-wake emissions. It will also be significant for green shipping corridors as every corridor must demonstrate the feasibility of one or several proposed fuel pathways, fuel availability, and bunkering infrastructure.

3.5 Bunker management and energy replenishment for ships

Bunker management and energy replenishment are necessary procedures in the operating profile of any vessel. These procedures have been performed since the entry of the first steam engines. While bunkers refer to fuel aboard a vessel, bunker management refers to procuring, tracking, and transferring the fuel to a vessel (Veson Nautical 2023). Various factors, such as the type of fuel used, the size of the ship, and the operational area, influence the nature of bunker management and energy replenishment processes for ships. The merchant fleet primarily relies on large refueling hubs along the most heavily traversed trading routes and near highly trafficked ports. Vessels engaged in liner traffic typically have a pre-determined refueling strategy that involves long-term contractual agreements with a limited number of selected ports. The significance of bunker management and replenishment in commercial maritime shipping organizations lies in its substantial relative cost compared to the overall operations of the vessel and its sustainability implications, particularly concerning the emissions produced by conventional fuels.

3.5.1 Bunkering strategies

Three main strategies are used for bunkering a vessel. A vessel can either be supplied with fuel by a Shore-to-Ship (PTS) operation, usually in ports, Ship-to-Ship (STS), or Truck-to-Ship (TTS) operations.

Port-to-Ship

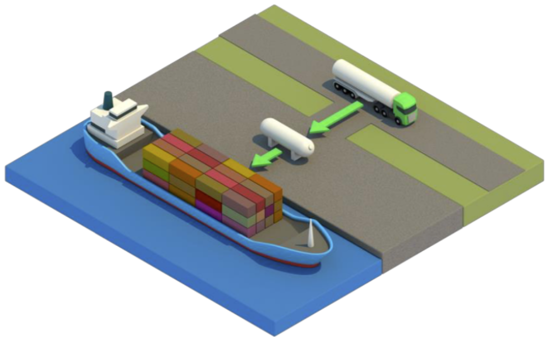


Figure 3.8: Port-to-Ship bunkering (DNV-GL 2014).

In a PTS operation, fuel is transported from a stationary fuel terminal, which is situated near or within the port gates, to a vessel docked at a nearby quay via a piping system. The fuel terminal usually has a capacity that can accommodate multiple vessels and can be serviced by either a bunkering vessel or trucks, depending on the type of fuel being offered. PTS-bunkering has several advantages, including its design flexibility, which can meet the need of a wide range of customers, and its potential to supply higher flow rates compared to TTS-bunkering, thus reducing the time vessels spend on bunkering operations. However, PTS-bunkering has limited geographical flexibility, requiring a fixed location near a dock or quay. Additionally, vessels must arrange to be at the loading quay for fuel transfer, which may result in extended port stays if bunkering cannot be performed concurrently with other activities (DNV-GL 2014).

Ship-to-ship and underway replenishment

(a) Ship-to-Ship bunkering (Almeida 2014).

(b) Underway replenishment (UK Ministry of Defence 2023).

Figure 3.9: STS bunkering strategies.

In an STS-bunkering operation, fuel transfers from a dedicated vessel or barge, which carries fuel as its cargo, to another vessel for use as fuel. It provides similar advantages to PTS-bunkering in flow rates and capacity but has greater location flexibility, as it can be performed either in port or at sea. STS-bunkering can be an attractive option for vessel operators as it eliminates the need to enter a port solely for refueling and offers greater logistical flexibility through simultaneous bunkering with other activities. However, potential hazards are associated with STS-bunkering, such as excessive movement between the bunker and receiving vessels, high sea states, and ship collisions. Effective management and mitigation of these risks are crucial for ensuring STS-bunkering operations' safe and efficient design and operation (DNV-GL 2014).

A variant of STS-bunkering operations is Underway replenishment (UNREP). It refers to transferring fuel from one vessel to another while both vessels are underway at sea. This form of bunkering dates back to 1899 but only became a standard procedure in the early 20th century. Navy forces have extensively used the procedure to extend their capabilities at sea (Pike 1999). UNREP is not commonly used in commercial shipping as it is a capital-intensive and operational complex procedure. However, this type of energy replenishment might prove crucial as vessels operating on low volumetric density energy carriers may see the need for more flexible replenishment operations.

Truck-to-Ship

TTS-bunkering is the process of transferring fuel from a truck's storage tank to a vessel docked at a quay. It offers high flexibility to ship operators, owners, ports, and other bunkering sites as the operation can, in practice, take place at any quay or dock. However, TTS-bunkering offers a lower fuel transfer capacity than PTS- and STS-bunkering. It may also complicate demonstrating sufficient safety as the bunkering operation may vary in location and procedures. Another concern about the bunkering operation is a lack of understanding among stakeholders, particularly truck drivers who are not permanent members. As a result, these drivers may not be familiar enough with safety requirements, potentially exacerbating hazardous situations (DNV-GL 2014).

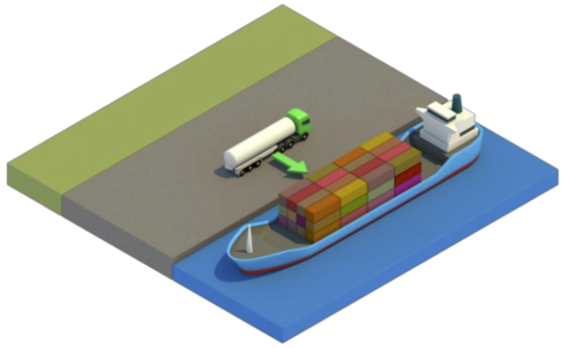


Figure 3.10: Truck-to-Ship bunkering (DNV-GL 2014).

3.6 Offshore energy replenishment

Offshore energy replenishment refers to the process of providing fuel or power to vessels while at sea. As introduced in 3.5.1, this technology already demonstrates success through UNREP of naval ships. However, the technology could expand beyond an STS-bunkering process offshore. Offshore energy production has seen significant growth in the last decade with the entrance of offshore wind turbines and pilot studies on floating solar panels. Integrating offshore energy replenishment with existing offshore energy production could help create a more sustainable and efficient energy system, making it a key solution for reducing the impact of shipping on the environment. It could be the missing piece of the puzzle for the successful operation of zero-emission vessels.

3.6.1 Why offshore energy replenishment in green corridors?

Zero-emission technology and sufficient bunkering infrastructure will be critical requirements for the success of green shipping corridors. However, utilizing these technologies will, in most instances, result in a reduction in operational range. This is mainly because several alternative fuels have a lower volumetric density than traditional fuels, meaning they will require bigger fuel tanks occupying more space in the vessel's hull to fulfill the same demand as conventional fueled vessels. In reality, it will become a trade-off between operational range and cargo carrying capacity, and vessel owners must find a satisfactory balance between these parameters. Offshore energy replenishment could solve this problem by offering energy en route to the destination. It will be especially suitable for trading routes spanning longer distances with limited access to onshore ports such as the Asia-US and US-Europe routes. Offshore energy replenishment will, however, not be that suitable for routes on local and regional levels as these usually consist of several ports capable of supplying energy.

3.6.2 Offshore energy replenishment and production concepts

The industry is investigating several concepts and strategies for offshore energy production and replenishment. Many of the concepts concentrate on energy generation and replenishment of electrical- or hydrogen-powered vessels. However, offshore production of other e-fuels, such as ammonia, is being investigated. Today's bunkering infrastructure is heavily connected to the demand for carbon-based fuels in the large shipping hubs of the world. By utilizing the significant growth of offshore renewable energy, it is possible to decentralize energy replenishment by producing fuel and energy offshore. The following chapter will overview some of the conceptual energy production and replenishment options currently being investigated.

Offshore energy hubs

Offshore energy hubs could be an important measure for the success of offshore energy replenishment and, thereby, green shipping corridors. It is considered an energy connection unit where multiple energy carriers can be converted, conditioned, and stored (Geidl et al. 2007). These hubs are expected to serve as connection points and storage sites for energy produced from offshore renewables, as direct energy supply can be challenging to obtain due to wind power volatility. However, it is also being investigated whether these hubs can utilize energy from offshore renewable to produce e-fuels. Hydrogen can, for instance, be produced at the energy hub by electrolysis of the electricity generated from connected offshore wind turbines. In a Haber-Bosch process, ammonia can then be formed from the hydrogen produced by adding nitrogen via air separation. Several studies on this type of energy hub concept have been performed. Thommessen et al. (2021) conclude in their techno-economic system analysis of an offshore energy hub that this concept is technically feasible with all necessary technologies available and already used in smaller-scale projects. This concept can create synergies between the oil and gas, fuel, and electricity sectors leveraging all three sectors in different ways. It will be reasonable to assume that zero-emission vessels also can take advantage of such energy hubs demonstrating storage, production, and distribution by using them as replenishment facilities. Figure 3.11 showcases a conceptual offshore hydrogen production unit.

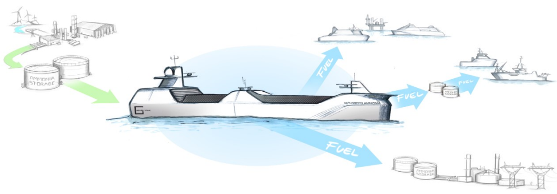
Figure 3.11: Offshore energy hub concept (Tractebel 2020).

Energy replenishment vessels

Several projects investigating the use of vessels to supply energy to other vessels have seen the light in recent years. Norway is at the forefront of this area, with two conceptual vessels proposed. Grieg Edge and Wärtsila Norway jointly run a project to launch *MS Green ammonia*- the world's first GHG-free tanker in 2024 (ZEEDS 2023). This concept emphasizes an ammonia-fueled tanker that will distribute ammonia from proposed factories to various locations and end-users along the coast of Norway. The vessel will also be capable of supplying ammonia through a STS operation as described in Chapter 3.5.1. Figure 3.12b illustrates the proposed concept.

Ulstein is also present with its launch of a new vessel concept called *Thor*, claiming to be shipping's silver bullet. It is a multi-purpose vessel concept that will enable energy replenishment and supplies in remote offshore areas while facilitating rescue operations and research tasks. Central for the concept, it will feature nuclear technology through a Thorium Molten Salt Reactor (MSR) to generate clean electricity (ULSTEIN 2022b). MSR is a safe, efficient, and operationally proven solution that works by dissolving Thorium in liquid salt. The subsequent chain reaction heats the salt, generating steam to power a turbine and generate electricity. This technology will enable the vessel to operate as a portable power and charging station for battery-driven vessels (ULSTEIN 2022b). Aside from zero emissions and remote replenishment, research, and rescue capabilities, the vessel's MSR could serve as an emergency power supply for areas affected by natural disasters, epidemics, or conflicts. Similarly, the abundant power supply could produce alternative or synthetic fuels via CO2 refinery (ULSTEIN 2022a). A concept such as the Ulstein Thor, illustrated in Figure 3.12a, could enable the successful operation of battery- and alternative fuel-powered vessels in green corridors as it can offer flexible energy replenishment.

(a) Ulstein *Thor* vessel concept (ULSTEIN 2022b).



(b) *MS Green Ammonia* concept (ZEEDS 2023).

Figure 3.12: Energy replenishment vessel concepts.

Floating offshore wind as a fuel production facility and recharging hub

As an alternative to separate offshore energy hubs, research into using offshore floating wind turbines for purposes other than electricity generation is underway, with varying approaches and goals. However, all of the current proposed concepts are based on utilizing energy generated by offshore wind turbines. One of the concepts under consideration is the production of large-scale green hydrogen from floating offshore wind. The *ERM Dolphyn* concept is based on a modular design that integrates electrolysis and a wind turbine on a moored floating substructure to produce hydrogen from seawater using wind power as the energy source. It is an integrated system that aims to combine all the technologies required to bring together the most recent floating wind and hydrogen production technologies, allowing offshore resources to contribute to large-scale hydrogen production (ERM 2023). It is reasonable to assume that this concept can further develop to include ammonia production by, e.g., integrating a Haber-Bosch process module. Figure 3.13 highlights an overview of the current concept.

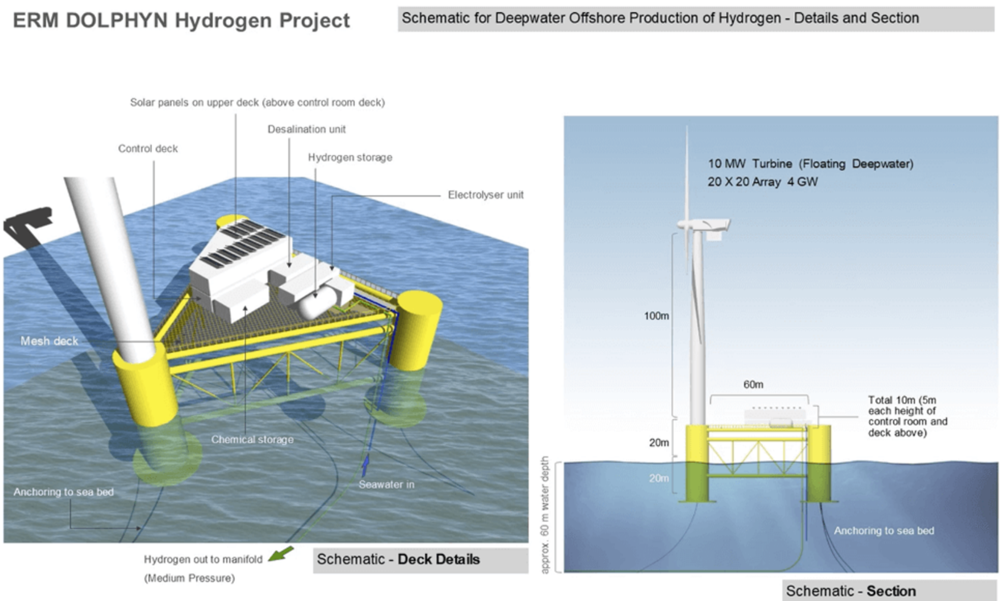


Figure 3.13: Hydrogen production from offshore wind concept (Wren and Christensen 2021).

The shipping giant A.P. Moller-Maersk and the renewable energy company Ørsted are also investigating further use of offshore wind. They have investigated the possibility of integrating an offshore charging device into the grid of offshore wind farms through a joint venture. Initially, it is a charging buoy connected to an offshore wind turbine that can bring green electricity directly to smaller offshore wind farm service vessels. However, the buoy will also aim to service larger vessels in a long-term perspective (Ørsted 2020). Figure 3.14 illustrates the concept.

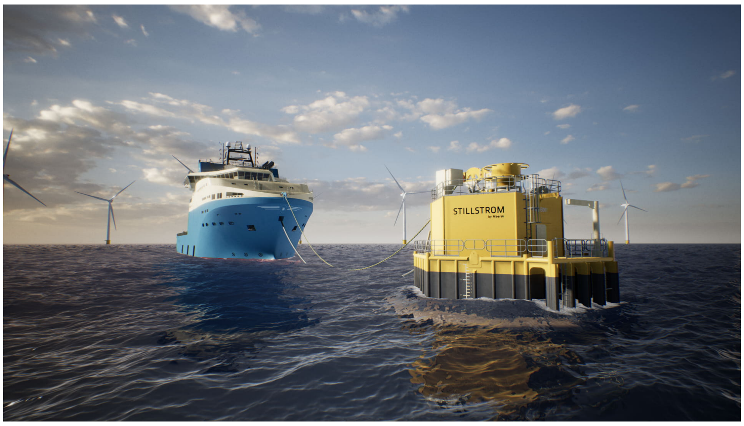


Figure 3.14: Maersk & Ørsted energy buoy concept (The Maritime Executive 2022).

Floating ammonia production unit

Existing competence in oil and gas floating production is now being utilized to develop new concepts for offshore floating production of alternative fuels. An example of such an initiative is the joint venture between Netherland-based SwitchH2 and Norway-based BW Offshore. The companies have come together to develop a NH_3 FPSO concept which will be built through the conversion of an existing very Large Crude Carrier (VLCC) or as a newbuild (DNV 2023a). By utilizing power from a wind farm, the unit will produce hydrogen by electrolysis of seawater and nitrogen through an air separation unit, combining these into an ammonia gas production unit. The ammonia will be stored in the hull and subsequently offloaded to an ammonia carrier. Offloading of ammonia will happen through a floating hose in a STS-bunkering operation. Furthermore, the production unit will be permanently moored but can be relocated if necessary (DNV 2023a). Even though the concept intends to distribute ammonia to a carrier vessel, it will be reasonable to assume that the concept could serve as an offshore bunkering unit for ammonia-fueled vessels. Figure 3.15 showcases the conceptual design.

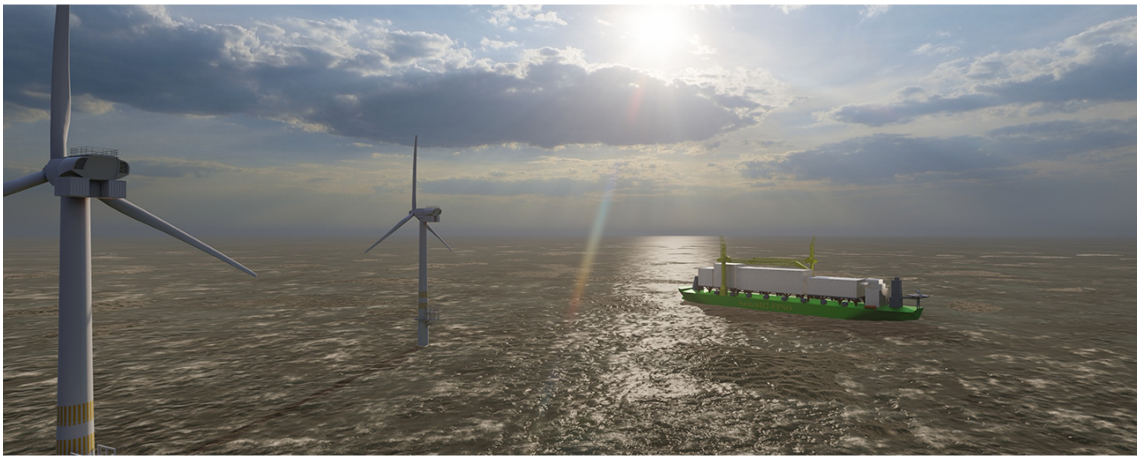


Figure 3.15: Floating ammonia production unit concept by SwitchH2 and BW Offshore (DNV 2023a).

Chapter 4

Methodology

Locating the optimal location of energy replenishment in a green corridor can be obtained through different approaches. The viability of green shipping corridors will depend on a successful transition from fossil to green fuels while promoting the development of zero-emission vessels. These requirements will necessitate major infrastructure and vessel-specific decisions requiring significant capital investments. A suboptimal or inaccurate decision in the decision-making process may result in severe economic consequences for vessel owners, fuel providers, and other critical stakeholders in a corridor. However, by modeling decisions as a mathematical optimization problem, stakeholders can be provided with decision support. A model that outputs the optimal energy replenishment locations for a vessel in a green corridor can be valuable in developing a specific shipping route suitable for zero-emission vessels.

Based on these considerations, the following chapter will introduce operations research and relevant approaches to support the initial problem. Optimization in maritime applications is often related to network optimization models. The current state-of-the-art network methodologies are an enormous field, and this chapter only scratches the surface by introducing three central methodologies widely applied in maritime transportation. The methodologies include the shortest path problem (SPP), vehicle routing problem (VRP), and facility location problem (FLP). The FLP will be particularly central as such a method is highly relevant to the thesis' objective. However, the models in this thesis share several elements from both VRP and SPP, as these present basic structures for optimizing maritime transportation problems.

4.1 Operation research

The rise of large and complex organizations in the modern era has increased the division of labor and management responsibilities. However, this has created new concerns, such as the independence of components within an organization, which leads to cross-purposes and difficulties in effectively allocating resources. These issues and the need for a more effective solution led to the development of operations research (OR) (S.Hillier and J. Lieberman 2015). OR can be traced back to the British and American military services during World War II, when a scientific approach was used to allocate resources effectively in military operations (Assad and Gass 2011). The success of OR during the war II led to its application outside of the military, and the improvement of OR techniques and the advent of the computer revolution facilitated its rapid growth. Today, millions of people have access to OR software, from mainframes to laptops, to solve a wide range of OR problems (S.Hillier and J. Lieberman 2015).

Operations Research is a scientific approach to problem-solving in manufacturing, finance, transportation, and healthcare organizations. OR employs a research-based method to carefully observe, formulate, and collect data on a problem before building a mathematical model that captures the essence of the problem. The model is then validated through experiments and tests, and if successful, it provides decision-makers with positive and understandable solutions (S.Hillier and J. Lieberman 2015). Figure 4.1 further illustrates the main procedures in OR. Operation research takes an organizational perspective and strives to resolve conflicts of interest among components that benefit the whole organization. The main goal of OR is to find the best solution possible, which necessitates a collaborative approach involving individuals with diverse backgrounds in mathematics, statistics, economics, computer science, engineering, and other fields (S.Hillier and J. Lieberman 2015).

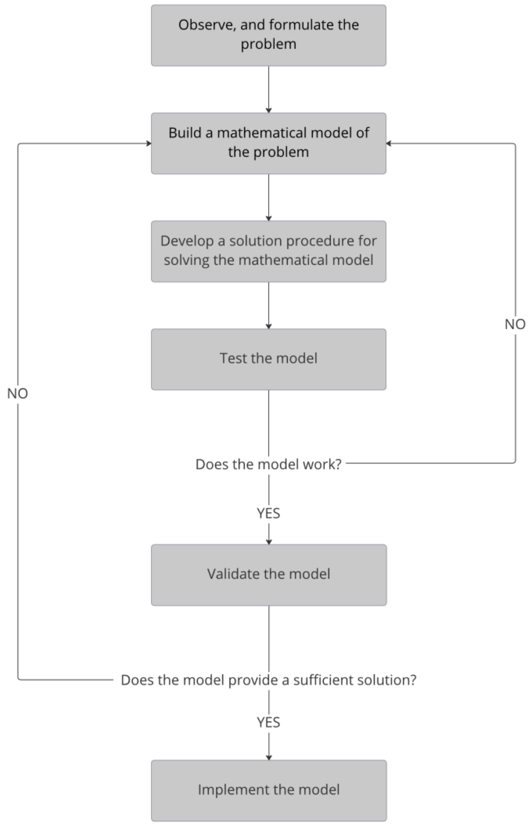


Figure 4.1: Main steps in Operation Research.

4.2 Network optimization

Networks can be found in a variety of settings and under varying forms. Transportation, electricity, and telecommunication are all examples of networks we use daily. Networks are also present in other areas such as production, distribution, project planning, facilities location, resource management, supply chain management, and financial planning. To put it another way; Networks are everywhere and highly valuable because they provide powerful visual and conceptual support for illustrating the relationships between the components of systems. For these reasons, they are applied in practically every sector of scientific, social, and economic effort (S.Hillier and J. Lieberman 2015).

A network consists of a set of nodes and a set of arcs connecting the nodes together. In the context of networks for electricity and energy distribution, telecommunication, and even computer networks, nodes and arcs have their natural physical explanation. In problems within transportation and distribution, however, one can, e.g., define nodes as production and inventory facilities, depots, docking stations, or customers. In these problems, Arcs can represent possible transport and distribution opportunities (Lundgren et al. 2010). Network problems are problems with an underlying network structure. Most of these problems require some flow moving across the network, resulting in a network flow problem. For these situations, both demand and supply of the flow can be expressed by describing the flow strength to and from the node, and on the arcs, costs, and capacities directing and restricting the flows on the arcs can be defined. The network structure must sometimes be provided, requiring careful modeling and description of nodes and arcs to obtain a network representation. Nodes and arcs can also be used to describe logical structures among a set of activities and occurrences. A network representation can facilitate modeling opportunities while providing a better overview and understanding of the problem. Furthermore, the network structure can be used to construct problem-solving algorithms (Lundgren et al. 2010).

Lundgren et al. (2010) classify network problems into two categories: how to utilize networks in an optimal way and how to design networks in an optimal way. The task in the first category is to identify how the flow should be transported in the network given a set of nodes with specified supply and demand and arcs with specified costs and capacities. An example of a problem in this category is the SPP. A solution for the second network problem category is reached by selecting a subset of the available nodes and arcs. Typically, it is also crucial to determine the optimal way to transport a given flow through the network constructed by nodes and arcs (Lundgren et al. 2010). This category includes both the VRP and the FLP. The following sections will go through SPP, VRP, and the FLP in greater detail.

4.2.1 Shortest path problem

The shortest path problem (SPP) is one of the most fundamental problems in network optimization. It frequently appears as a subproblem in more significant network problems, requiring a thorough understanding of the problem and the ability to solve it efficiently (Lundgren et al. 2010). The main objective of the SPP is to find the shortest path, i.e., the path with the minimum total distance, between a start node, n_s, and an end node, n_t in a network. The optimization is often performed based on cost, time, distance, or other values that can be summarized over the arcs between the nodes in the network. To solve a SPP, three conditions need to be satisfied for the network:

- All arcs are directed.
- The end node, n_t must be reached from the start node, n_s.
- There are no cycles with negative costs.

Arcs must have an orientation or direction to be directed. However, directed arcs only allow flow in a specific direction. If some arcs are undirected, i.e., they do not have a direction, the undirected arc can be replaced with two directed arcs, where each new directed arc has the same cost as the undirected arc. Finding the shortest path in a network will not be achievable if no path exists from node n_s to n_t as there is no feasible solution to the problem in such a case. Moreover, cycles are referred to as connected arcs starting and ending in the same node (Lundgren et al. 2010). Finding optimality for a shortest path problem can be achieved by using different algorithms. These algorithms will not be discussed in further detail, but we acknowledge *Dijkstra's algorithm*, *Ford's algorithm*, and the *Floyd-Warshall algorithm* as the most important ones.

4.2.2 Vehicle routing problem

The Vehicle Routing Problem (VRP) is an optimization problem that aims to discover the most effective delivery or pickup routes from a central depot to a group of geographically dispersed customers. The routes must meet various limitations, such as vehicle capacity, route length, time constraints, and customer precedence relations (Laporte 2007). This type of problem is encountered daily by thousands of distributors worldwide and has significant economic importance. A typical example of VRPs in the real world is the distribution of newspapers to retailers and food and drinks to grocery stores. VRPs are also highly relevant in the shipping industry and are a common problem for shipowners with a fleet of vessels that need to serve a demand or supply from a set of ports.

The Traveling Salesman Problem (TSP) is generalized in the VRP. TSP's primary goal is to identify the shortest, least expensive route that visits all customers exactly once and then returns to the starting node. VRP, on the other hand, seeks to satisfy a given demand at each node with a certain vehicle capacity. Such circumstances will necessitate using more than one vehicle, raising two important questions: Which consumer will be served by which vehicle? And how should the clients on each route be visited (Ormevik 2022).

There are two approaches to modeling the VRP. It can be modeled similarly to the TSP by ensuring that all visited nodes are included in the model, or it can be modeled with pre-generated routes that ensure all nodes are visited and are valid for the given restrictions. The following will give a general model of the TSP, beginning with the model notation:

Sets:

V - Set of vehicles.

N - Set of nodes (customers).

Parameters:

c_{ijv} - Cost of traveling between node i and j using vehicle v.

K_v - Capacity of vehicle v.

D_i - Demand of node (customer) i.

Decision variable:

$$u_{ijv} \text{ - } \begin{cases} 1 & \text{if vehicle } v \text{ uses arc } (i,j). \\ 0 & \text{otherwise.} \end{cases}$$

Mathematical formulation:

$$MIN\ Z = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} c_{ijv} u_{ijv} \tag{4.1}$$

S.t:

$$\sum_{j \in N} u_{1jv} \leq 1, \qquad v \in V \tag{4.2}$$

$$\sum_{j \in N} \sum_{v \in V} u_{ijv} = 1, \qquad i \in N \setminus \{1\} \tag{4.3}$$

$$\sum_{j \in N} u_{ijv} = \sum_{j \in N} u_{ijv}, \qquad i \in N \setminus \{1\}, v \in V \tag{4.4}$$

$$\sum_{i \in N} \sum_{j \in N]} D_i u_{ijv} \leq K_v, \qquad v \in V \tag{4.5}$$

$$u_{ijv} \in \{0, 1\}, \qquad i, j \in N, v \in V \tag{4.6}$$

The objective function, equation 4.1, minimizes the overall routing cost, i.e., the cost of traveling all selected arcs for all vessels. Equation 4.2 ensures that a vehicle leaves the depot at most once. Equation 4.3 ensures that all nodes are visited exactly once. Equation 4.4 is a flow constraint and ensures that every vehicle that visits a node also leaves the node. Equation 4.5 ensures that for each vehicle, the sum of customer demands on a route must not exceed the vehicle's capacity. Finally, equation 4.6 is the binary constraint. Subtour elimination constraints must also be defined for each vehicle. These restrictions prevent the model from constructing routes between nodes that do not visit the depot. However, the model does not include these limitations. The general VRP model presented above can further be interpreted to address other important aspects of a routing problem. Possible extensions include the cost of using the vehicles, time constraints related to the specific routes, and vehicle capacity restrictions. Despite numerous alternative formulations and extensions, the model presented through equations 4.1 to 4.6 serves as a basis for many real-life routing problems within maritime transportation.

As global transportation, both on- and offshore, is evaluating alternative low-carbon or zero-emission fuels, the Green Vehicle Routing Problem (G-VRP) has seen the light. It is a variant of the traditional VRP that intends to assist organizations with alternative fuel-powered vehicle fleets in addressing challenges caused by restricted vehicle driving range and limited refueling infrastructure (Erdoğan and Miller-Hooks 2012). Erdoğan and Miller-Hooks (2012) formulated the G-VRP as a mixed-integer linear program with a complete graph of vertices representing customer locations, alternative fuel stations, and a depot. It seeks a set of vehicle tours with minimum distance, each starting at the depot, visiting customers within a pre-defined time limit, and returning to the depot without exceeding the vehicle's driving range, which will depend on the fuel tank capacity. Furthermore, each tour may include a stop at one or more fuel stations, allowing the vehicle to refuel on the route. Model notation and solution heuristics will not be further investigated in this thesis. However, we acknowledge G-VRP as an important problem that can provide decision support to zero-emission vehicles and ships.

4.2.3 Facility location problem

The facility location problem (FLP) is a commonly used integer programming model and is a central area within location science. FLPs consist of determining the" best" location for one or several facilities or equipment in order to serve a set of demand points, often referred to as customers (Laporte et al. 2015). The model is widely used in several industries and societies to find the optimal location of, e.g., power plants, warehouses, polling stations, and waste collection stations (Cantlebary and Li 2022). FLPs and location science have their fundament in four basic problems: the p-median, p-center, fixed charge facility, and the covering location problem. The p-median problem aims to choose p facilities among a set of n candidates that minimize the cost of supplying a finite set of customers. The chosen facilities p are often referred to as *medians*, hence *p-median*. p-center problems, however, is a minmax solution consisting of a set of p points where the goal is to minimize the maximum distance between a demand point and the closest point belonging to the set of p. In a fixed-charge facility location problem, there is a finite set of customers with a demand for service and a finite set of potential locations for the facilities offering service to the customers. When deciding where to locate facilities that provide service, it often appears that a customer can receive this service only if the person is located less than a certain distance from the nearest facility. An example of such a scenario is the ambulance's ability to arrive within a certain time based on the patient's location. When this is the case, the patient is said to be" covered," and we have a covering location problem (Laporte et al. 2015).

In addition to the four fundamental facility location problems, separating capacitated and uncapacitated FLPs is common. A capacitated FLP applies constraints to each facility's production and transportation capacity. This may result in customers not being supplied by the most immediate facility as this facility might not be able to satisfy the demand. On the other hand, an uncapacitated facility problem assumes that each facility can produce and distribute an unlimited amount of product. In this case, The optimal solution will result in customers being supplied by the lowest cost, usually by the nearest facility (Cantlebary and Li 2022). This thesis will not provide further detail into the area of location science. However, a common generic FLP description will be presented.

Lundgren et al. (2010) formulate the capacitated FLP as the problem of choosing a set of facilities, e.g., terminals, depots, or distribution centers, designed to support a set of customers. There are m potential facilities and n customers. Furthermore, each facility, i, has a given capacity, s_i, and each customer, j has a given demand d_j. The problem involves several costs, including the fixed cost f_i if facility i is used and a unit cost C_{ij} for each unit transported between facility i and customer j. The problem can be mathematical formulated with the following model notation:

Decision variables:

$$y_i \text{ - } \begin{cases} 1, & \text{if facility } i \text{ is open.} \\ 0, & \text{otherwise.} \end{cases}$$

x_{ij} - Flow from facility i to customer j.

Mathematical formulation:

$$MIN\ Z\ = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} + \sum_{i=1}^{m} f_i y_i \tag{4.7}$$

S.t:

$$\sum_{j=1}^{n} x_{ij}\ \leq\ s_i y_i, \qquad i = 1, ..., m \qquad (Supply) \tag{4.8}$$

$$\sum_{j=1}^{m} x_{ij}\ =\ d_j, \qquad j = 1, ..., n \qquad (Demand) \tag{4.9}$$

$$x_{ij}\ \geq\ 1, \qquad i = 1, ..., m; \qquad j = 1, ..., n \tag{4.10}$$

$$y_i \in \{0, 1\}, \qquad i = 1, ..., m \tag{4.11}$$

Equation 4.7 is the objective function that aims to minimize the cost of serving all customers. Equation 4.8 ensures that the amount of transported units from a facility does not exceed the facility's capacity. Equation 4.9 ensures that each customer's demand j is fulfilled. Equation 4.10 ensures that the flow from facility i to customer j must be non-negative. Equation 4.11 is the binary constraint.

The FLP has been developed and extended over many years with new models and problem definitions entering the research area. As discussed in Chapter 4.2.2, the entrance of alternative-fueled vehicles has resulted in a shorter range and new VRP models. However, FLP models are also affected by the vehicle range issue resulting in new approaches beyond the traditional problem introduced in this chapter. An example of an extended FLP is the development of a location-allocation model for "flow capturing." Hodgson and Rosing (1992) first introduced this model, assuming that instead of locating central facilities to serve demand at fixed points in space, the model aims to serve demand consisting of flows from an origin to a destination along their shortest path. Central for the flow capturing model is the following assumption; if a flow passes just one refueling facility along its path, it is considered covered. This assumption does not hold when alternative-fueled vehicles are utilized due to the limited range. It might be necessary to stop at more than one facility along the route to successfully refuel the entire path, depending on the vehicle range, path length, and node spacing.

In response to the concerns arising from the initial flow capturing model, Kuby and Lim (2005) introduced The Flow Refueling Location Model (FRLM), which optimally locates refueling stations in a network to maximize the total flow volume refueled. Through model development and implementation, they could use a combination of different facilities to refuel network paths and an algorithm for determining which facilities are feasible at each path.

Studies like Kuby and Lim (2005) extending the FLP and investigating refueling have centered on large road networks onshore and the vehicles using them. It is reasonable to assume that many of the characteristics of these studies can be transferred to maritime applications and ship routing problems, as shipping creates massive networks only with different parameters. Vessels often have a fixed trading route, making them less flexible compared to vehicles. Choosing another path may result in significant switch-ups in the vessel's trading system and can also lead to increased costs. Ship routing is, therefore, a whole research area of its own. However, the general FLP model presented in this chapter can be a good reference for further development and application in maritime cases.

4.3 Solver programs

Optimization problems can vary in complexity, influencing the solution procedures. Some problems can easily be solved using analog techniques such as e.g., simplex tableau. However, they often tend to escalate concerning complexity resulting in the problems being very time-consuming to solve. Luckily digital tools and solvers are available, making the solution procedures much more efficient. Numerous optimization solvers and software can solve defined, correctly implemented problems. For instance, Excel and its built-in solver have been widely used for solving numerous optimization problems. Solvers such as Gurobi, Xpress, CPLEX, and sciPy are also commonly used. These separate themselves from Excel by being compatible with different programming languages, usually Python, C, or MATLAB. Figure 4.2 illustrates the solver programs' role and how we implement them into the operation research methodology. The optimization models presented in this thesis will utilize the combination of Gurobi optimization and Python as the solvers of choice.

Gurobi is an optimization software developed by *Gurobi Optimization LLC*. It is considered one of the fastest and most diverse optimization software able to solve a broad range of problem types. Problems such as linear, mixed-integer, quadratic, mixed-integer quadratic, quadratically constrained, and mixed-integer quadratically constrained programming can all be resolved by the software. Gurobi is accessible through the use of Python (Educative 2023).

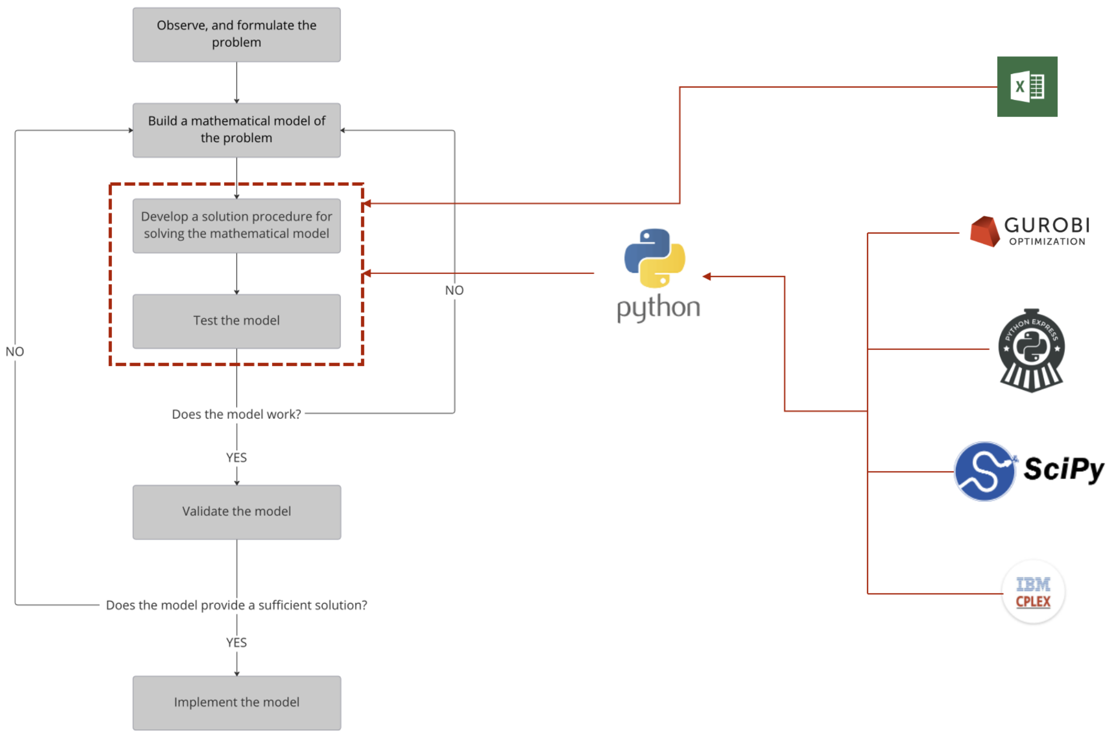


Figure 4.2: Using solver programs in operation research.

Chapter 5

Initial models - optimal location of energy replenishment for a single vessel

The following chapter describes the initial steps in developing a mathematical optimization model to resolve the optimal locations for energy replenishment. Creating mathematical optimization models is commonly a step-by-step process that begins with creating a simplified model that covers the fundamental characteristics and central concepts of the problem. The model can then be expanded by adding more parameters, variables, and constraints, resulting in a more detailed and precise description of the real-world problem.

The mathematical model presented in this chapter and later extended in Chapters 6 and 7.2 is relatively generic. Therefore, it shares similarities with previous work and studies of optimal location of energy replenishment. Similar models have, e.g., previously been used in (Haahjem 2022) and shall be understood as a model applicable to various networks and vessel segments. However, the degree of applicability on different node networks and environments of replenishment locations is relatively limited, and this thesis goes further in researching different networks applied to the model as a part of the model validation process.

5.1 General problem description

The initial models assume a single alternative-fueled vessel sailing between two ports. Due to limited tank size volumes, the vessel cannot complete the journey without replenishing energy between the ports. Energy can be replenished at one or more locations between the ports. The models intend to determine the optimal locations for energy replenishment operations and the vessel's required energy storage capacity. Increasing the vessel's energy storage capacity will result in penalties due to reduced cargo-carrying capacity. Furthermore, the vessel has a designated energy consumption per distance traveled and a sailing cost. It is also assumed that the energy, i.e., fuel, will be delivered to the replenishment locations from a fuel hub facility located a predetermined distance from the replenishment locations. The distance between the replenishment location and the fuel hub will determine the cost of this operation.

5.2 Model 1 - Energy replenishment at one specific location

The first model presented is a simplified version of the general problem. The model will serve as a basis for further expansions and model development.

5.2.1 Model description

An available cargo vessel utilizing alternative fuel is on its way from a port of origin, O, to a port of destination, D. The vessel cannot complete the journey unless an energy replenishment operation is performed at a specific location, L , along the route. The vessel has a flexible energy storage capacity, k^{ES}, that depends on the sailing distance to the replenishment location L. The amount of cargo the vessel can transport is affected by its energy storage capacity and modeled as a lost opportunity cost per unit energy storage capacity of the vessel, C^{LOC}. Furthermore, the energy storage capacity will be limited by the vessel's total storage capacity, K^V, which includes the combined cargo and energy storage space. The vessel will also have a sailing cost, CV, and energy consumption per distance traveled, E^V. The model aims to identify the optimal location, L , for the energy replenishment operation. A fuel hub, H, services the replenishment location, and there is a cost of supplying fuel to the location, C^{FHS}. The distance determines the cost of fuel supply, D_{Hj}, between the fuel hub and the energy replenishment location. Figure 5.1 shows an illustrative overview of the model.

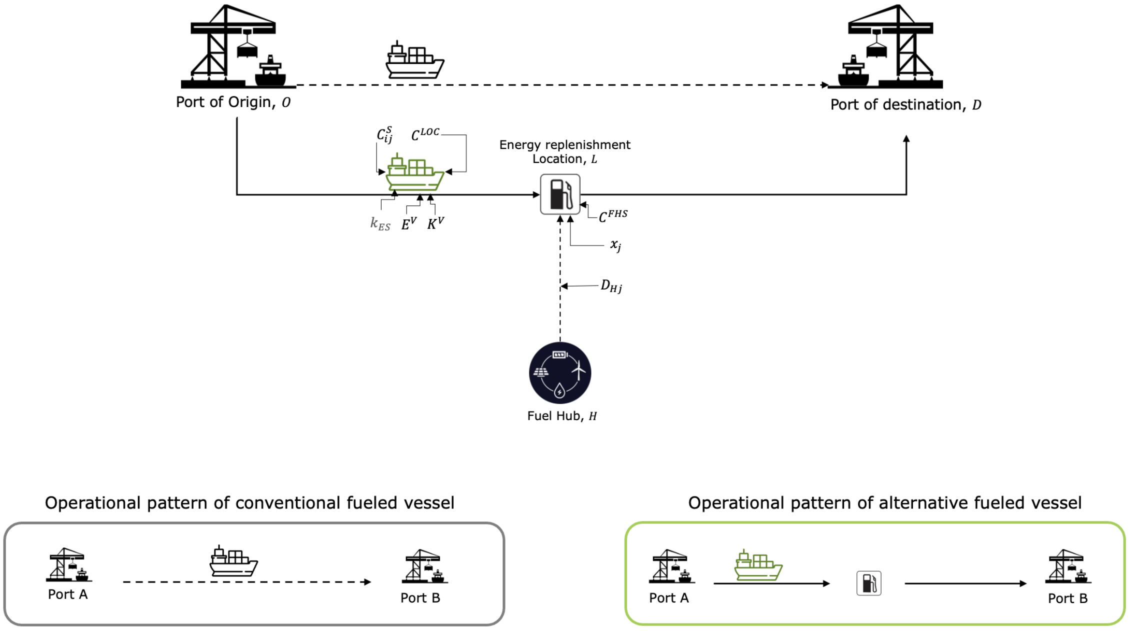


Figure 5.1: Illustrative overview of initial model 1.

5.2.2 Model notation

Sets:

N - Set of Nodes including port of origin, O and port of destination, D, fuel hub H and energy replenishment location, L.

L - Set of energy replenishment locations including the fuel hub, H $L \subset N$.

Parameters:

C_{ij}^S - Cost of sailing from node i to j, for the vessel [$\$/NM$].

C^{LOC} - Lost opportunity cost per unit energy storage capacity for the vessel [$\$/m^3$].

C^{FHS} - Cost of supplying fuel from the fuel hub per distance unit [$\$/NM$].

K^V - Total storage capacity of vessel [m^3].

E^V - Energy consumption per distance unit traveled for the vessel [m^3/NM].

D_{ij} - Sailing distance between node i and node j [NM].

Variables:

$$x_j - \begin{cases} 1 & \text{if the vessel visits the energy replenishment station } j. \\ 0 & \text{otherwise.} \end{cases}$$

k^{ES} - Energy storage capacity of the vessel [m^3].

5.2.3 Mathematical model

This section presents the mathematical formulation of energy replenishment in one specific location. By using the notation introduced in 5.2.2, the problem can be formulated using the following model.

$$MIN\ Z = \sum_{j \in L} C^S_{ij}(D_{Oj} + D_{jD})x_j + C^{LOC}k^{ES} \ + \sum_{j \in L/\{H\}} C^{FHS} D_{Hj} x_j \tag{5.1}$$

Subject to:

$$\sum_{j \in L} x_j = 1, \tag{5.2}$$

$$E^V D_{ij} x_j \leq k^{ES}, \qquad i \in N/\{L\}, j \in L \tag{5.3}$$

$$0 \leq k^{ES} \leq K^V, \tag{5.4}$$

$$x_j \in \{0, 1\}, \qquad j \in L \tag{5.5}$$

Equation (5.1) represents the objective function. It aims to minimize the total cost of the system, which consists of three cost components: the sailing cost between the port and the energy replenishment location, the lost opportunity cost due to the amount of space the energy storage occupies onboard the vessel, and the cost of supplying fuel to the replenishment location from the fuel hub. Constraint (5.2) ensures that only one replenishment location is visited in one of the optional locations. Moreover, the vessel cannot take on a voyage that demands more energy than the energy storage capacity of the vessel, and is ensured through constraint (5.3). Additionally, the energy storage capacity of the vessel has to be non-negative and cannot exceed the total storage capacity of the vessel. This is handled through equation (5.4). Finally, equation (5.5) is the binary constraint that ensures that the variables x_j either take the value 1 or 0.

5.2.4 Illustrative validation of the model 1

Before moving on to the next stage of model development, the initial model must be validated and thoroughly tested to ensure it performs as intended. There are several methods for validating models. The model will be solved and tested using a combination of *Gurobi Optimization* and Python, as discussed in Chapter 4.3. It is also preferable to visualize the results of the developed model because data visualization can help individuals better understand the functionality of the model and the data presented.

The initial logistical optimization problem is graphically illustrated by building a coordinate system representing a trading route between two ports. The coordinate systems' origin and destination port and fuel hub are fixed points. Furthermore, a small arbitrary grid of coordinates between the three fixed locations is established. These shall be considered optional locations for the vessel's single energy replenishment operation. The model has been given arbitrary parameter values for illustration purposes. As a preliminary step in the model development process, the model is first tested for different values of the fuel supply cost from the fuel hub to the optimal replenishment location, C^{FHS}. The findings are illustrated in Figures 5.2 to 5.5.

Table 5.1: Model 1 parameters, test 1.

Parameter	Value
C^S	10,0
C^{LOC}	5,0
C^{FHS}	**2,0**
K^V	50,0
E^V	3,0
Resulting k^{ES}	**15,0 m^3**

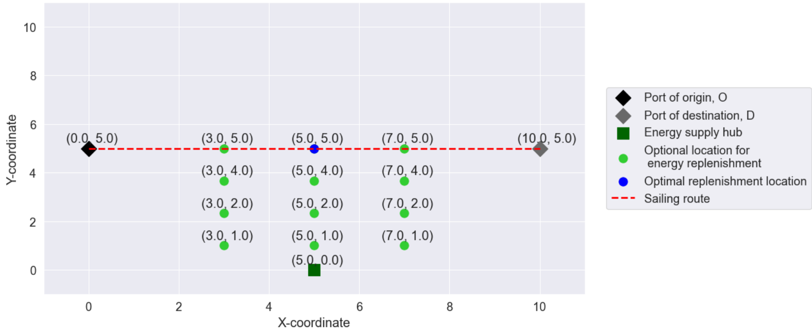


Figure 5.2: Model 1 solution, test 1.

Table 5.2: Model 1 parameters, test 2.

Parameter	Value
C^S	10,0
C^{LOC}	5,0
C^{FHS}	**5,0**
K^V	50,0
E^V	3,0
Resulting k^{ES}	**15.5 m^3**

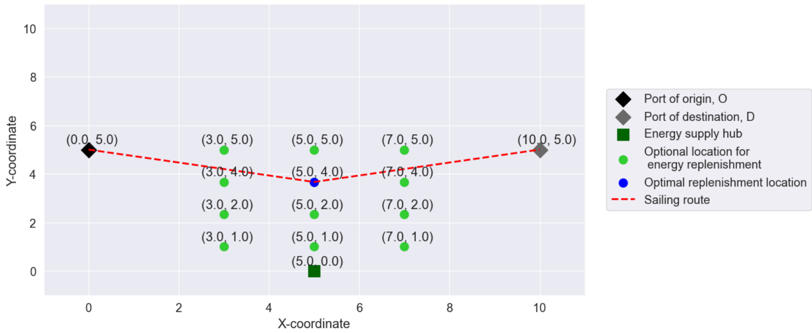


Figure 5.3: Model 1 solution, test 2.

Table 5.3: Model 1 parameters, test 3.

Parameter	Value
C^S	10,0
C^{LOC}	5,0
C^{FHS}	**15,0**
K^V	50,0
E^V	3,0
Resulting k^{ES}	**17,0 m^3**

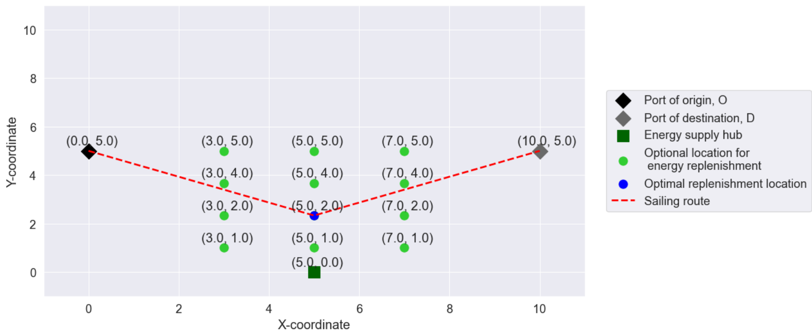


Figure 5.4: Model 1 solution, test 3.

Table 5.4: Model 1 parameters, test 4.

Parameter	Value
C^S	10,0
C^{LOC}	5,0
C^{FHS}	**20,0**
K^V	50,0
E^V	3,0
Resulting k^{ES}	**19.2 m^3**

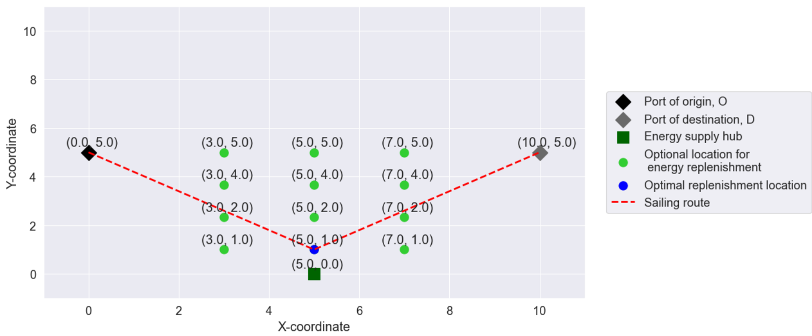


Figure 5.5: Model 1 solution, test 4.

Testing the model for different arbitrary values of C^{FHS} might not be sufficient to verify whether the model performs as intended. For that reason, our analysis continues by testing the model for different values of the vessel-related costs, C^{LOC} and C^S. Model results are illustrated in figures 5.6 to 5.9.

Table 5.5: Model 1 parameters, test 5.

Parameter	**Value**
C^S	**2,0**
C^{LOC}	**5,0**
C^{FHS}	20,0
K^V	50,0
E^V	3,0
Resulting k^{ES}	**19.2** m^3

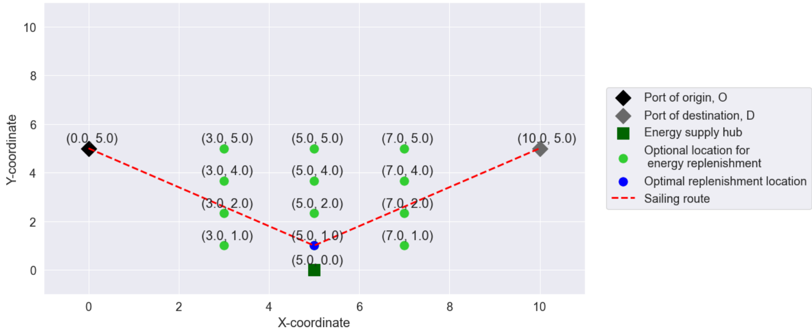


Figure 5.6: Model 1 solution, test 5.

Table 5.6: Model 1 parameters, test 6.

Parameter	**Value**
C^S	**5,0**
C^{LOC}	**10,0**
C^{FHS}	20,0
K^V	50,0
E^V	3,0
Resulting k^{ES}	**17,0** m^3

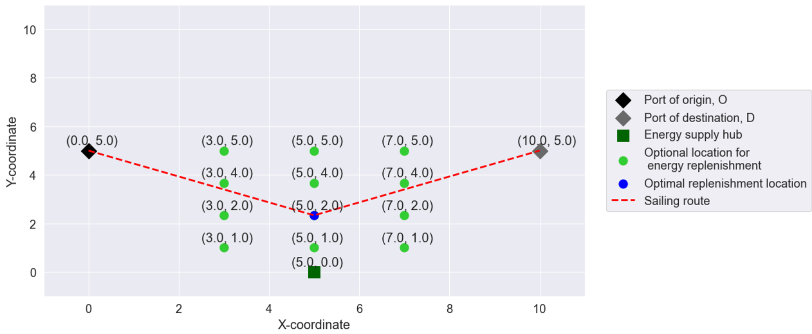


Figure 5.7: Model 1 solution, test 6.

Table 5.7: Model 1 parameters, test 7.

Parameter	**Value**
C^S	**10,0**
C^{LOC}	**20,0**
C^{FHS}	20,0
K^V	50,0
E^V	3,0
Resulting k^{ES}	**15.5** m^3

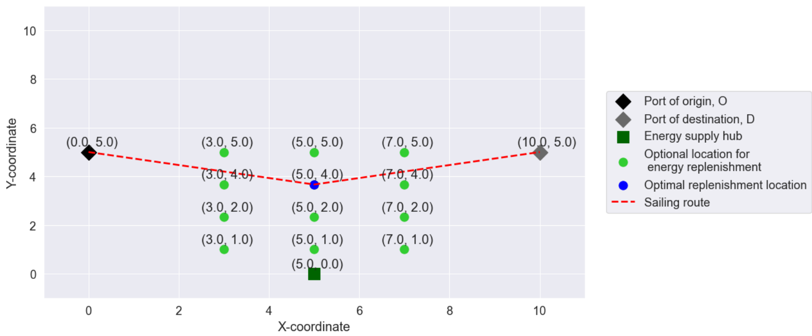


Figure 5.8: Model 1 solution, test 7.

Table 5.8: Model 1 parameters, test 8.

Parameter	**Value**
C^S	**30,0**
C^{LOC}	**35,0**
C^{FHS}	20,0
K^V	50,0
E^V	3,0
Resulting k^{ES}	**15,0** m^3

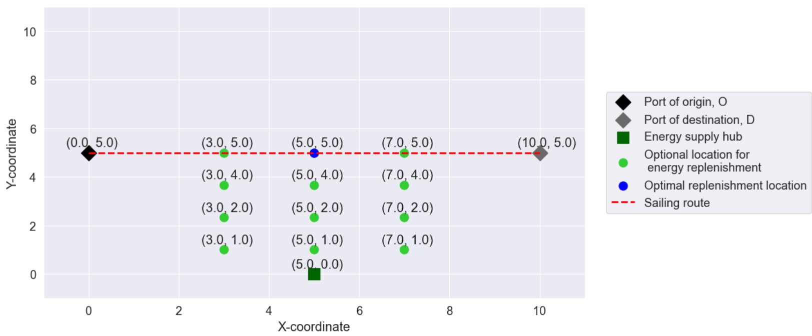


Figure 5.9: Model 1 solution, test 8.

As illustrated in figures 5.2 to 5.9, the initial model can identify the optimal location for energy replenishment between the ports and the fuel hub based on the set of optional locations given to the model. It also handles the trade-off between fuel hub-related costs and vessel-related costs. As the cost of supplying fuel to the energy replenishment location rises, the optimal location for energy replenishment shifts closer to the fuel hub. Simultaneously, increasing vessel-related costs move the optimal replenishment location further away from the energy hub.

5.3 Initial model 2 - Network of energy replenishment locations

The initial model introduced in Chapter 5.2 must expand to simulate a more realistic scenario. Allowing the vessel to visit multiple locations for energy replenishment instead of only one location in the first model is an optional improvement. The new model extends the first one by allowing the vessel to make multiple stops for energy replenishment between ports and the fuel hub. As a result, the problem evolves into a network problem with nodes and associated arcs.

5.3.1 Model description

As for the initial scenario, a cargo vessel using alternative fuel is set to transport its cargo between two ports. However, the vessel can now visit multiple energy replenishment locations randomly distributed between the ports and the energy hub. By letting the vessel do so, a set of arcs, A, between the nodes adds to the model. Additionally, a set of nodes, N, which includes the port of origin, O, the port of destination, D, and the set of energy replenishment locations, L, which includes the fuel hub H, is proposed. The vessel will suffer a sailing cost, C^S_{ij}, a lost opportunity cost per unit energy storage capacity, C^{LOC}, and a cost of supplying fuel from the fuel hub to the replenishment location, C^{FHS}. However, a new cost parameter, C^{RLE}, is introduced for this model, describing the cost of establishing an energy replenishment location between the ports and the fuel hub. The vessel retains its total storage capacity, K^V, energy consumption per distance traveled, E^V, sailing distance, D_{ij} between each node in the network, and energy storage capacity, k^{ES}. In addition, the decision variable, x_j , is converted into a routing variable, x_{ij} , which determines which arcs the vessel will use and which replenishment locations it will visit. In addition, a new dependent variable, e_{ij}, is introduced to represent the vessel's energy consumption between nodes i and j. Figure 5.10 portrays an illustrative overview of the model.

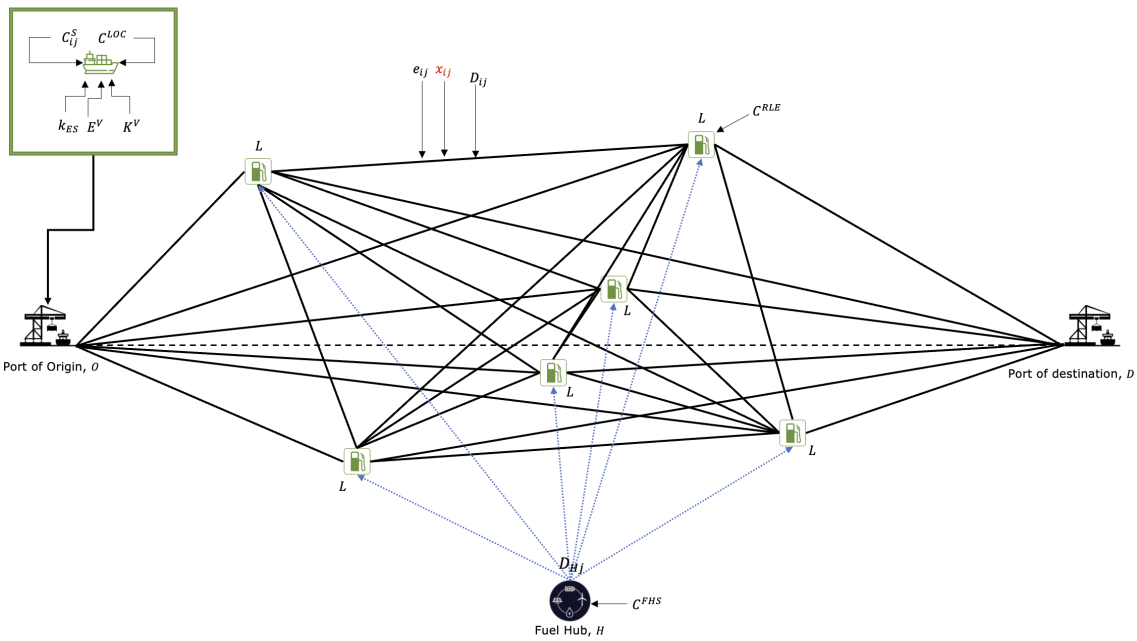


Figure 5.10: Initial model 2.

5.3.2 Model notation

Sets:

N - Set of Nodes including the port of origin, O and port of destination, D.

L - Set of energy replenishment locations including the fuel hub, H, $L \subset N$.

A - Set of arcs between nodes N.

Parameters:

C^S_{ij} - Cost of sailing from node i to j, for the vessel [$\$/NM$].

C^{LOC} - Lost opportunity cost per unit energy storage capacity for the vessel [$\$/m^3$].

C^{FHS} - Cost of supplying fuel from the fuel hub [\$].

C^{RLE} - Cost of establishing a energy replenishment location [\$].

K^V - Total storage capacity of vessel [m^3].

E^V - Energy consumption per distance unit traveled [m^3/NM].

D_{ij} - Sailing distance between node i and node j per distance unit [NM].

Variables:

$$x_{ij} \text{ - } \begin{cases} 1 & \text{if the vessel sail from node } i \text{ to node } j. \\ 0 & \text{otherwise.} \end{cases}$$

k^{ES} - Energy storage capacity of vessel [m^3].

e_{ij} - energy consumption for the vessel from node i to node j.

5.3.3 Mathematical formulation

This section presents the mathematical formulation of energy replenishment in a network of optional energy replenishment locations. By using the notation introduced in 5.3.2, the problem can be formulated using the following model:

$$MIN\ Z = \sum_{i,j \in A} C^S_{ij} D_{ij} x_{ij} + C^{LOC} k^{ES} \quad + \sum_{i \in N} \sum_{j \in L/\{H\}} (C^{FHS} D_{Hj} + C^{RLE}) x_{ij} \tag{5.6}$$

Subject to:

$$\sum_{j \in N} x_{Oj} - \sum_{j \in N} x_{iO} = 1, \tag{5.7}$$

$$\sum_{i \in N} x_{iD} - \sum_{i \in N} x_{Di} = 1, \tag{5.8}$$

$$\sum_{j \in L} x_{ij} = \sum_{j \in L} x_{ji}, \qquad i \in N \tag{5.9}$$

$$x_{ij} + x_{ji} \leq 1, \qquad (i,j) \in A \tag{5.10}$$

$$E^V D_{ij} x_{ij} = e_{ij}, \qquad (i,j) \in A \tag{5.11}$$

$$0 \leq e_{ij} \leq k^{ES}, \qquad (i,j) \in A \tag{5.12}$$

$$0 \leq k^{ES} \leq K^V, \tag{5.13}$$

$$x_{ij} \in \{0,1\}, \qquad (i,j) \in A \tag{5.14}$$

Equation (5.6) represents the objective function, which, like the first model, seeks to minimize total sailing costs and lost opportunity costs due to the amount of space alternative fuel storage takes up onboard the vessel. Furthermore, the objective function aims to reduce the cost of establishing an energy replenishment location and supplying fuel to the replenishment location from the fuel hub. Exact one arc can be active for the port of origin and destination. Such a requirement is ensured through constraints (5.7) and (5.8). In addition, the sum of inbound arcs must equal the sum of outbound arcs for every replenishment location. This is managed by constraint (5.9). Constraint (5.10) states that only one arc can connect two nodes together, while (5.11) defines the energy consumption for the vessel between node i to node j. Additionally, the energy consumption between each node must not exceed the energy storage capacity of the vessel. This is handled in constraint (5.12). Constraint (5.13) ensures that the energy storage capacity of the vessel has to be non-negative and cannot exceed the total storage capacity of the vessel. Equation (5.14) is the binary constraint.

5.3.4 Illustrative validation of model 2

The model presented in 5.3 will be validated using the same approach as the one utilized in the first model. Nevertheless, some adjustments have been made. An arbitrary number of coordinates are defined between the port of origin, the port of destination, and the fuel hub. However, in this case, the number of optional locations has increased. These coordinates are also randomly positioned between the three fixed points in the coordinate system. The randomly distributed coordinate network is generated to further validate how the model responds to different node networks. The input variables to the model are also arbitrarily selected for this case. Furthermore, the model is tested for different values of C^{LOC} as an increase in C^{LOC} indicates less energy storage capacity of the vessel. Figures 5.12 to 5.14 present the test results.

Table 5.9: Model 2 parameters, test 1.

Parameter	Value
C^S	10
C^{LOC}	**0,05**
C^{FHS}	3
K^V	30
E^V	5
Resulting k^{ES}	**30 m^3**

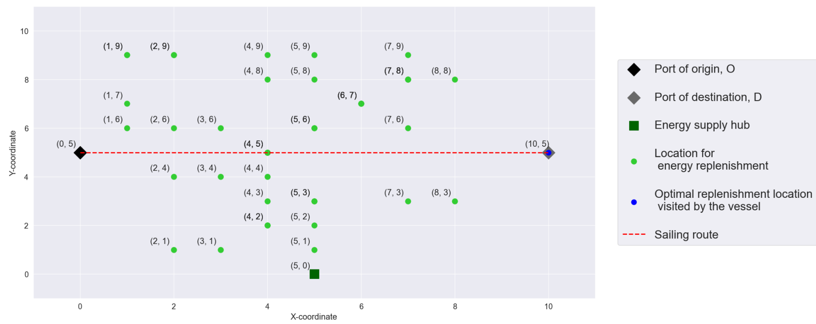


Figure 5.11: Model 2 solution, test 1.

Table 5.10: Model 2 parameters, test 2.

Parameter	Value
C^S	10
C^{LOC}	**2**
C^{FHS}	3
K^V	30
E^V	5
Resulting k^{ES}	**26,9** m^3

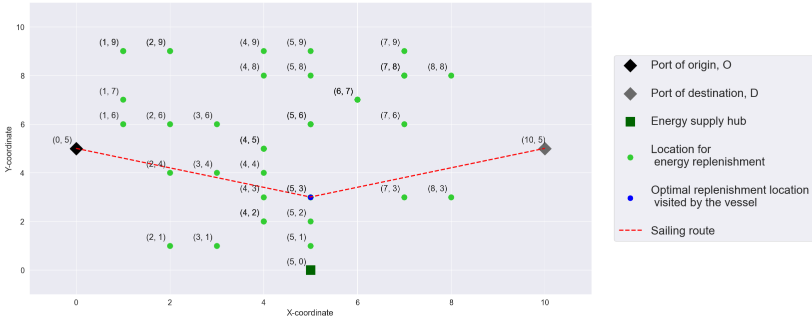


Figure 5.12: Model 2 solution, test 2.

Table 5.11: Model 2 parameters, test 3.

Parameter	Value
C^S	10
C^{LOC}	**10**
C^{FHS}	3
K^V	30
E^V	5
Resulting k^{ES}	**15,8** m^3

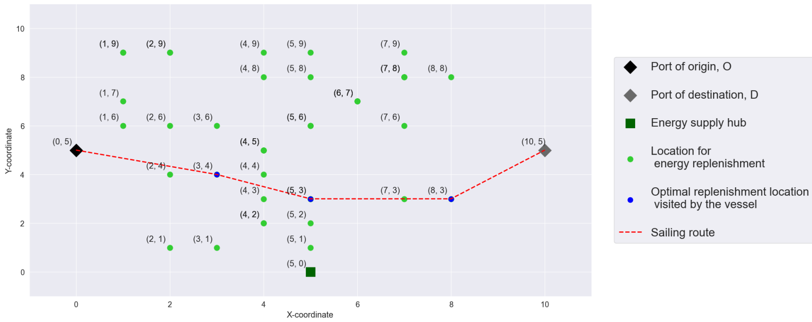


Figure 5.13: Model 2 solution, test 3.

Table 5.12: Model 2 parameters, test 4.

Parameter	Value
C^S	10
C^{LOC}	**30**
C^{FHS}	3
K^V	30
E^V	5
Resulting k^{ES}	**14,1** m^3

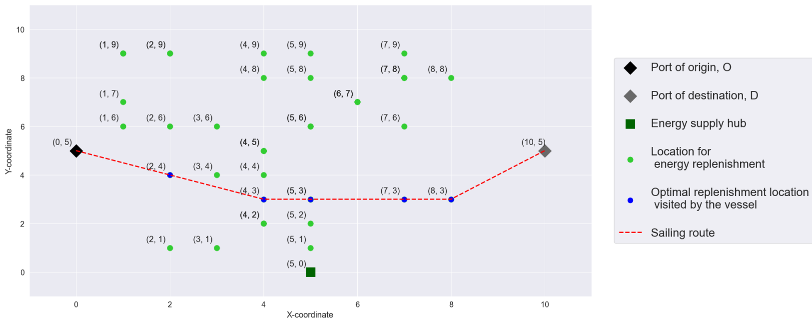


Figure 5.14: Model 2 solution, test 4.

Figure 5.11 illustrates a scenario where the lost opportunity cost, C^{LOC}, is set to a low value. With a lost opportunity cost of 0.05, the model identifies the optimal location for energy replenishment in the port of destination, D. It should also be noted that for the first test result, the energy storage capacity of the vessel, k^{ES} is equal to the total storage capacity of the vessel, K^V. In other words, the entire storage capacity of the vessel is occupied by fuel and fuel equipment in such a scenario. Such a result will not be realistic for a real-world case. However, it illustrates that an alternative-fueled vessel can make the voyage without replenishment if the energy storage capacity is big enough.

Continuing our analysis, figure 5.12 to 5.14 illustrates that by increasing the lost opportunity cost, the energy storage capacity of the vessel decreases, resulting in more locations for energy replenishment becoming part of the optimal solution. Figure 5.12 reveals that the model identifies one single replenishment location relatively close to the energy hub. Similarly, by increasing the lost opportunity cost to 10 and 30, the model adds more locations to the optimal solution, resulting in a decrease in energy storage capacity. Based on the test results, it is reasonable to conclude that the model performs as intended. However, we repeat that the input parameters are arbitrarily selected, and other input values may result in other solutions.

Chapter 6

Extended model - multi-hub, multi-vessel energy replenishment network

The models presented in Chapter 5 are a relatively simplified representation of the general problem description introduced in 5.1. They address a simple voyage between two ports with a visit to a specific location between the ports where energy replenishment takes place. In the long-term perspective, a green shipping corridor will consist of a network of ports and vessels. It is, therefore, only natural to strive to extend and develop the initial models into a model that better describes a realistic future scenario. A realistic green corridor scenario might see the entrance of multiple vessel types, fuel hubs, ports, and even bunkering vessels serving specific refueling locations. There are a lot of opportunities and possibilities arising from the concept of green shipping corridors. A step-by-step model development is therefore critical in order to model future scenarios. The following chapter will present an extended model of the initial models in Chapter 5, aiming to simulate a realistic green corridor scenario.

6.1 Model description

The extended model will be anchored in the two initial models presented in Chapter 5.1. However, some extensions have been made. In contrast to the first two models, the extended model now intends to handle a fleet of vessels sailing between multiple ports on each side of a green corridor. A realistic scenario might also see several fuel hubs available to supply the replenishment locations. For that reason, a second fuel hub is introduced. Introducing a fleet of vessels, more ports, and an additional fuel hub turns the problem into a multi-vessel, multi-hub, multi-port network problem. A new set, V, is introduced by extending the model to include multiple vessels. As a result, the characteristics of each vessel must be managed independently. However, this model handles this by assuming a homogeneous fleet of vessels to simplify the problem.

As for the initial models, each vessel will have a total storage capacity, K_v^V, an energy storage capacity, k_v^{ES}, and a given energy consumption per distance traveled, E_v^V. In addition, each vessel will have an associated sailing cost, C_{ijv}^S, and a lost opportunity cost per unit energy storage capacity, C_v^{LOC}. Furthermore, each fuel hub will have a cost of supplying fuel from the fuel hub per distance unit, C^{FHS}. In addition, each fuel hub will now have a set of associated locations that the fuel hub will need to supply with energy. The extended model is also allowed to decide whether an energy replenishment location is set to be established in one of the optional locations or not. This opportunity will introduce a new decision variable, l_j, which takes the value one if an energy replenishment location is established in one of the optional locations and zero otherwise. Establishing an energy replenishment location will also introduce a fixed cost, C^{RLE}. Figure 6.1 provides an illustrative overview of the extended model.

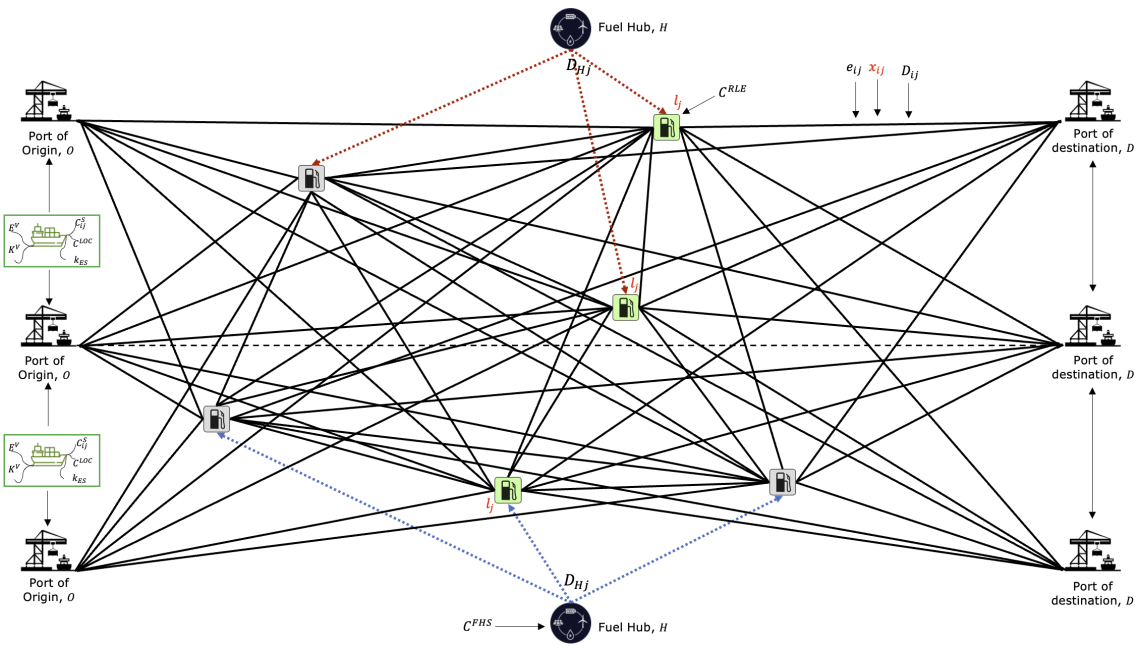


Figure 6.1: Extended model illustration

6.2 Model Notation

Sets:

N - Set of Nodes including port of origin for vessel v, O_v and port of destination for vessel v, D_v.

L - Set of energy replenishment locations including the fuel hubs serving node j, H_j, $L \subset N$.

A - Set of arcs between nodes N.

V - Set of vessels v.

Parameters:

C^S_{ijv} - Cost of sailing from node i to j, for vessel v [$\$/NM$].

C^{LOC}_v - Lost opportunity cost per unit energy storage capacity for vessel v [$\$/m^3$].

C^{FHS} - Cost of supplying fuel from the fuel hub per distance unit [$\$/NM$].

C^{RLE} - Cost of establishing a energy replenishment location [$\$$].

K^V_v - Total storage capacity of vessel v [m^3].

E^V_v - Energy consumption per distance unit traveled for vessel v [m^3/NM].

D_{ijv} - Sailing distance between node i and node j for vessel v [NM].

Variables:

$$x_{ijv} - \begin{cases} 1 & \text{if vessel } v \text{ sail from node } i \text{ to } j. \\ 0 & \text{otherwise.} \end{cases}$$

$$l_j - \begin{cases} 1 & \text{if an energy replenishment location } l \text{ is established in one of the optional locations } j. \\ 0 & \text{otherwise.} \end{cases}$$

k^{ES}_v - Energy storage capacity of vessel v [m^3].

e_{ijv} - energy consumption from node i to node j for vessel v.

6.3 Mathematical model

$$MIN\ Z = \sum_{j \in A} \sum_{v \in V} C^S_{ijv} D_{ijv} x_{ijv} + \sum_{v \in V} C^{LOC}_v k^{ES}_v + \sum_{j \in L/\{H_j\}} (C^{FHS} D_{H_j jv} + C^{RLE}) l_j \tag{6.1}$$

Subject to:

$$\sum_{j \in N} x_{O_v jv} - \sum_{j \in N} x_{iO_v v} = 1, \qquad v \in V \tag{6.2}$$

$$\sum_{i \in N} x_{iD_v v} - \sum_{i \in N} x_{D_v iv} = 1, \qquad v \in V \tag{6.3}$$

$$\sum_{j \in L} x_{ijv} = \sum_{j \in L} x_{jiv}, \qquad i \in N, v \in V \tag{6.4}$$

$$x_{ijv} + x_{jiv} \leq 1, \qquad (i,j) \in A, v \in V \tag{6.5}$$

$$E^V_v D_{ijv} x_{ijv} = e_{ijv}, \qquad (i,j) \in A, v \in V \tag{6.6}$$

$$0 \leq e_{ijv} \leq k^{ES}_v, \qquad (i,j) \in A, v \in V \tag{6.7}$$

$$x_{ijv} \leq l_j, \qquad i \in N, j \in L, v \in V \tag{6.8}$$

$$0 \leq k^{ES}_v \leq K^V_v, \qquad v \in V \tag{6.9}$$

$$x_{ijv} \in \{0,1\}, \qquad (i,j) \in A, v \in V \tag{6.10}$$

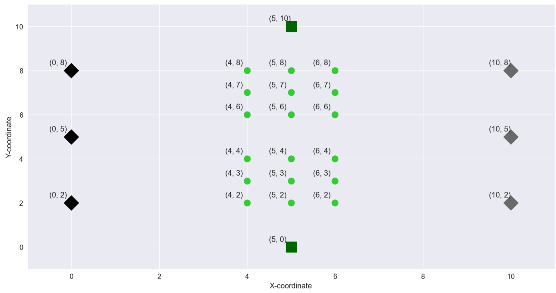
$$l_j \in \{0,1\}, \qquad j \in L \tag{6.11}$$

Equation (6.1) is the objective function which, as for the initial models, aims to minimize the total cost. It includes the total sailing cost and lost opportunity cost due to the space occupied by the alternative fuel onboard the vessel. The objective function also aims to minimize the cost of establishing fuel hubs and supplying fuel from the fuel hub to the energy replenishment locations. Equation (6.2) ensures that there can only be one active arc from the port of origin for vessel v. Simultaneously, equation (6.3) ensures that exactly one arc can be active for the port of destination for vessel v. Moreover, the sum of inbound arcs must be equal to the sum of outbound arcs for every replenishment location. This is ensured in equation (6.4). Additionally, only one arc can connect two nodes for each vessel v, and is ensured through constraint (6.5). Equation (6.6) defines the energy consumption of vessel v between two nodes. At the same time, constraint (6.7) ensures that the energy consumption between each node must not exceed the energy storage capacity of the vessel. Furthermore, an energy replenishment location is established in node j only if a vessel v visits the node. This is ensured through constraint (6.8). Constraint (6.9) ensures that the energy storage capacity of the vessel has to be non-negative and cannot outdo the total storage capacity of vessel v. In conclusion, constraints (6.10) and (6.11) are binary constraints.

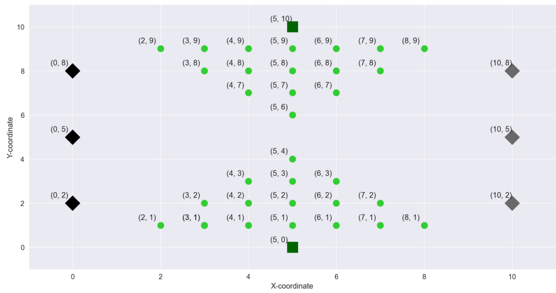
6.4 Illustrative model validation

The same procedure as the initial models is used to validate the extended model. A coordinate system representing a trading route is constructed with ports and fuel hubs being fixed locations. The fleet size is set to three identical vessels, making a voyage between a port of origin, O_v, and a port of destination, D_v. Each vessel is assigned to a specific port of origin and a corresponding destination port. Each vessel can, however, visit one of the other ports before ending its voyage in its assigned destination port. Furthermore, a set of optional locations for energy replenishment are generated with a connecting fuel hub servicing the locations.

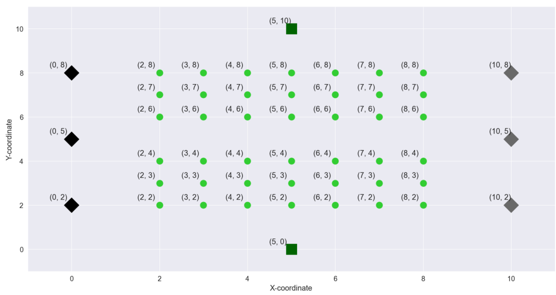
It may be interesting to see if the extended model can handle various replenishment location environments in which the vessels must operate. In other words, different formations of replenishment locations in the coordinate system. In a green corridor, various node environments can simulate various scenarios. It may be reasonable to assume scenarios in which bunkering vessels operate out from the fuel hub with a limited range, which means they reach a maximum distance from the fuel hub due to energy storage capacity. It can also be other circumstances that cause only a specific set of energy replenishment locations to be available. For that reason, the extended model will be tested for four different node environments, as shown in Figure 6.2.



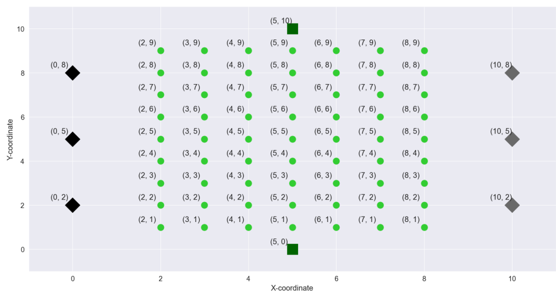
(a) Node environment 1, 18 replenishment locations.



(b) Node environment 2, 32 replenishment locations.



(c) Node environment 3, 42 replenishment locations.



(d) Node environment 4, 63 replenishment locations.

Figure 6.2: Four different node environments for the extended model.

The model presented in Chapter 6.3 will be tested and evaluated for all four node environments illustrated in figure 6.2. For every scenario, the model will be tested for arbitrarily input values in addition to different values of C^{FHS}, as this variable influences the number of optimal replenishment locations identified by the model. The following subsequent chapters will present the test results.

6.4.1 Node environment 1 - 18 alternative replenishment locations

The first scenario emphasizes the node environment illustrated in figure (6.2a), where each fuel hub services nine locations. The input data to the model is presented in table 6.1a and 6.1b respectively, and the results are illustrated through figure 6.3, 6.4, and 6.5.

(a) Extended model 1, test parameters.

Parameter	Value
C^S	1
C^{LOC}	6
C^{FHS}	**1 / 2 / 5**
C^{RLE}	1
K^V	30
E^V	2

(b) Coordinates for the port of origin and port of destination.

Vessel number, v	O_v coordinate	D_v coordinate
1	$(0, 2)$	$(10, 8)$
2	$(0, 5)$	$(10, 5)$
3	$(0, 8)$	$(10, 2)$

Table 6.1: Input data for the extended model, node environment 1.

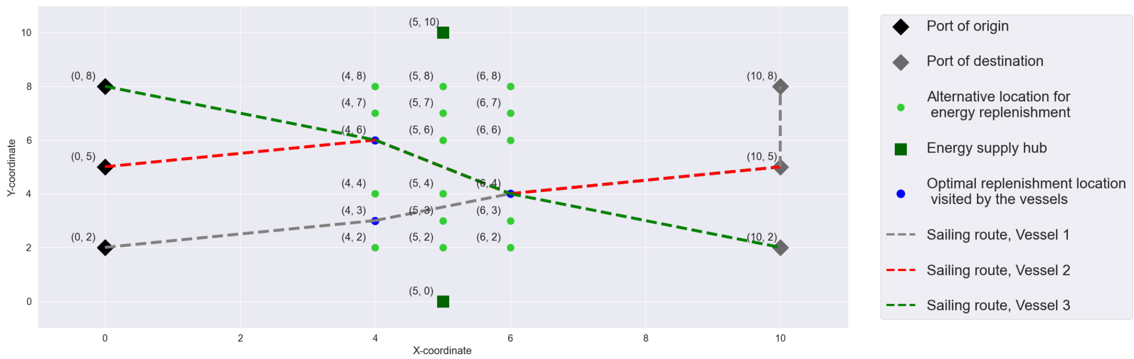


Figure 6.3: Extended model 1 results, $C^{FHS} = 1$.

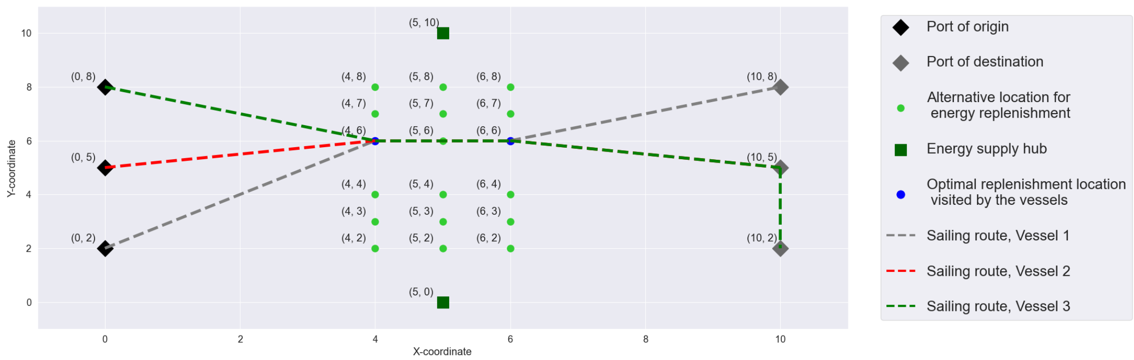


Figure 6.4: Extended model 1 results, $C^{FHS} = 2$.

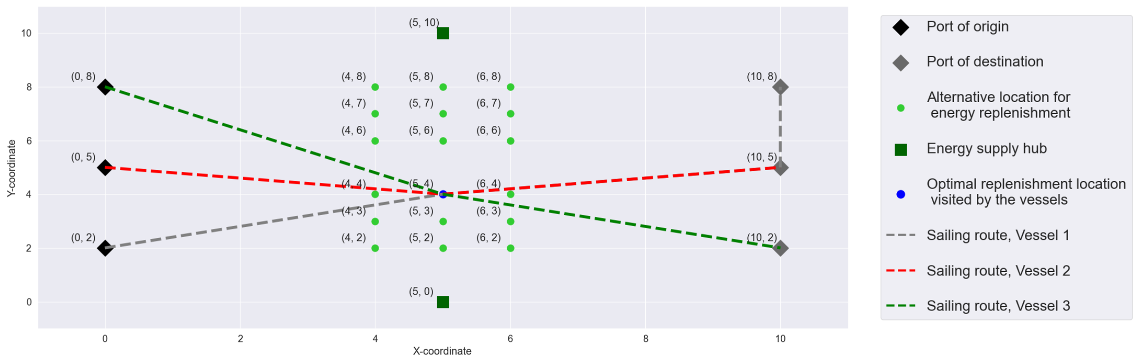


Figure 6.5: Extended model 1 results, $C^{FHS} = 5$.

Test results

The test results for the first node environment are summarized in table 6.2:

Table 6.2: Extended model 1 results.

Vessel number, v	C^{FHS}	**Sailed route**	**Resulting** k^{ES}
1	1	$(0,2),(4,3),(6,4),(10,5),(10,8)$	8.246
1	2	$(0,2),(4,6),(6,6),(10,8)$	8.246
1	5	$(0,2),(5,4),(10,5)$	10.770
2	1	$(0,5),(6,4),(10,5)$	8.246
2	2	$(0,5),(4,6),(6,6),(10,5)$	8.246
2	5	$(0,5),(5,4),(10,5)$	10.198
3	1	$(0,8),(4,6),(6,4),(10,2)$	$8,944$
3	2	$(0,8),(4,6),(6,6),(10.2)$	8.944
3	5	$(0,8),(5,4),(10,2)$	12.806

Given a set of alternative locations for energy replenishment with a connecting fuel hub, the model can identify optimal locations visited by the vessels and the corresponding arcs used by each vessel, as shown in Figures 6.3, 6.4 and 6.5.

C^{FHS} is set to 1 for the first model test, establishing three optimal replenishment locations. Furthermore, the fuel hub in $(5,10)$ is responsible for serving the optimal location in $(4,6)$, whereas the fuel hub in $(5,0)$ serves the two other optimal locations identified by the model. It is also worth mentioning that location $(6,4)$ is the only one visited by all three vessels. The optimal locations for test number two decrease from three to two. Unlike in the first test, all vessels visit both optimal locations. It should also be noted that the optimal locations found are only serviced by one of the fuel hubs, namely the one in $(5,10)$. Only one optimal location is determined in the third test run. The fuel hub in services the location that all vessels visit.

The number of optimal locations found by the model decreases as C^{FHS} increases and will affect the overall cost, making it less appealing to establish new locations for energy replenishment. Furthermore, when energy replenishment options are limited, vessels must use longer arcs, resulting in a higher energy storage capacity requirement K^{ES}.

6.4.2 Node environment 2 - 32 alternative replenishment locations

As seen in figure 6.2b, the second node environment extends the number of alternative locations to 32 in the coordinate system, where each fuel hub can service 16 locations in a pyramid formation. The new node environment is tested and validated using the same procedure as in 6.4.1. The input data to the model is presented in table 6.3a and 6.3b. The results are illustrated through figure 6.6 and 6.7.

(a) Extended model 2, test parameters.

Parameter	Value
C^S	2
C^{LOC}	6
C^{FHS}	**1 / 10**
C^{RLE}	1
K^V	40
E^V	2

(b) Coordinates for the port of origin and port of destination.

Vessel number, v	O_v coordinate	D_v coordinate
1	$(0,2)$	$(10,8)$
2	$(0,5)$	$(10,5)$
3	$(0,8)$	$(10,2)$

Table 6.3: Input data for the extended model, node environment 2.

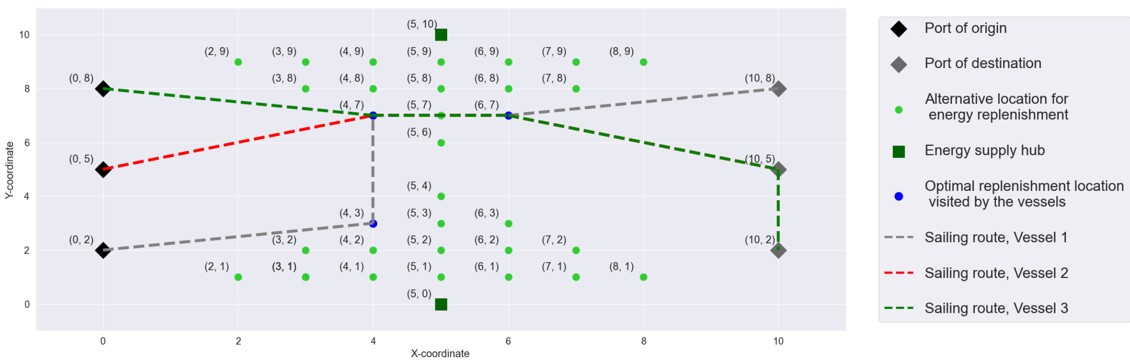


Figure 6.6: Extended model 2 results, $C^{FHS} = 1$.

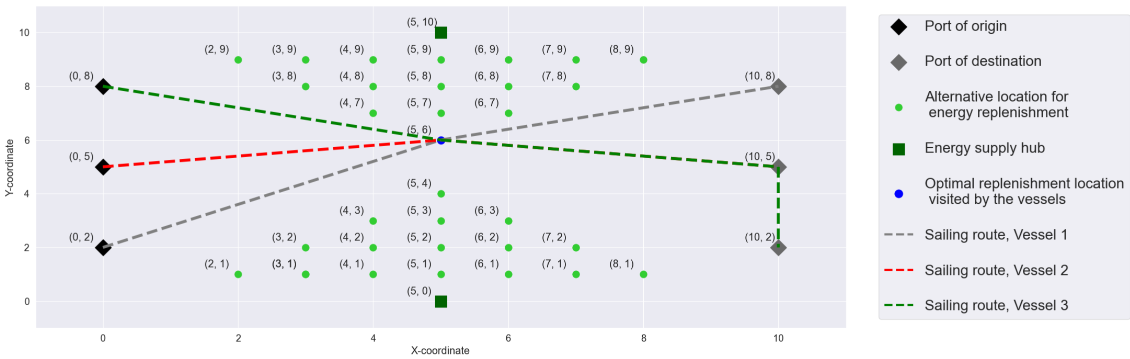


Figure 6.7: Extended model 2 results, $C^{FHS} = 10$.

Test results

The test results for the second node environment are summarized in table 6.4:

Table 6.4: Extended model 2 results.

Vessel number, v	C^{FHS}	**Sailed route**	**Resulting** k^{ES}
1	1	$(0,2),(4,3),(4,7),(6,7),(10,8)$	8.246
1	10	$(0,2),(5,6),(10,8)$	$12,806$
2	1	$(0,5),(4,7),(10,5)$	8.944
2	10	$(0,5),(5,6),(10,5)$	10.198
3	1	$(0,8),(4,7),(6,7),(10,5),(10,2)$	$8,944$
3	10	$(0,8),(5,6),(10,5),(10.2)$	$10,770$

Figures 6.6 and 6.7 show that the model can handle a new node environment of 32 locations. For the first test, C^{FHS} remains at 1, and the model, as expected, identifies three optimal locations for energy replenishment. Two optimal locations are serviced by the fuel hub in $(5,10)$, while the last one is serviced by the fuel hub in $(5,0)$. Furthermore, it follows that replenishment locations $(4,7)$ and $(6,7)$ serve all three vessels, whereas replenishment location $(4,3)$ serves only vessel 1.

By increasing C^{FHS} to 10, only one optimal location for energy replenishment is in the optimal solution. It is also once again demonstrated that fewer optimal energy replenishment locations in the network result in longer vessel sailing distances, which, as expected, increases the required energy storage capacity k^{ES}.

6.4.3 Node environment 3 - 42 alternative replenishment locations

The third node environment consists of 42 alternative locations, as seen in figure 6.2c. Each fuel hub now has the responsibility of serving 21 locations each. The model is tested in the new environment with the following input data:

(a) Extended model 3, test parameters.

Parameter	**Value**
C^S	3
C^{LOC}	6
C^{FHS}	**1 / 2 / 3 / 4**
C^{RLE}	1
K^V	35
E^V	2

(b) Coordinates for the port of origin and port of destination.

Vessel number, v	O_v **coordinate**	D_v **coordinate**
1	$(0,2)$	$(10,8)$
2	$(0,5)$	$(10,5)$
3	$(0,8)$	$(10,2)$

Table 6.5: Input data for the extended model, node environment 3.

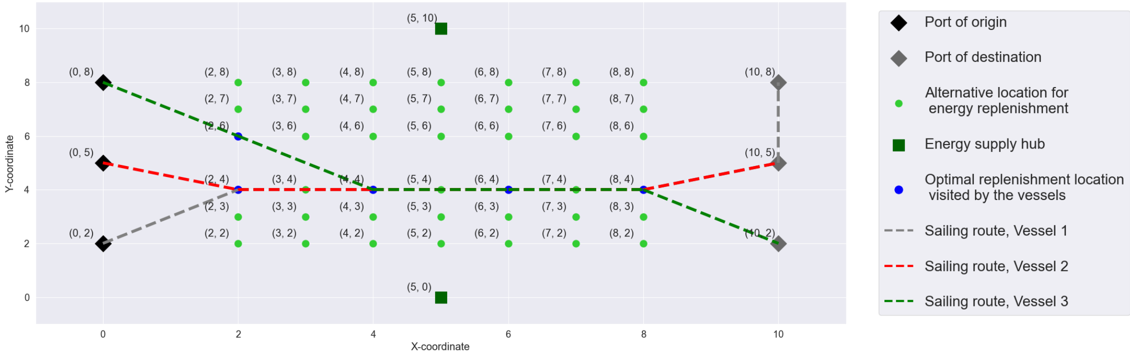


Figure 6.8: Extended model 2 results, $C^{FHS} = 1$.

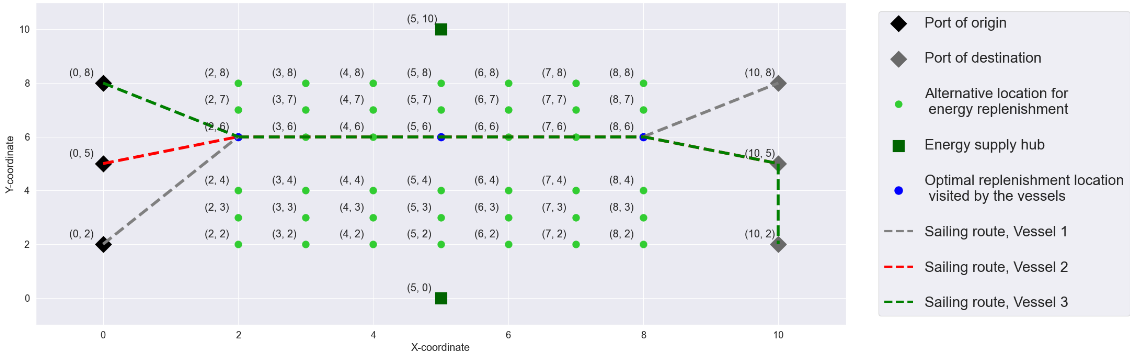


Figure 6.9: Extended model 2 results, $C^{FHS} = 2$.

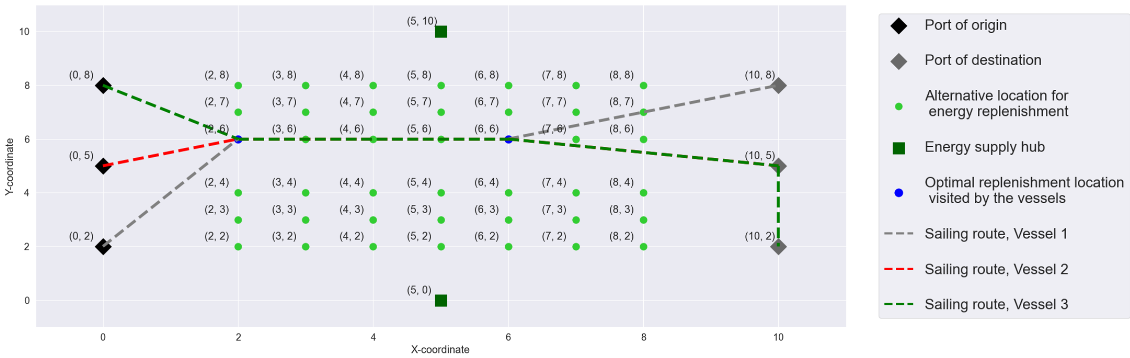


Figure 6.10: Extended model 2 results, $C^{FHS} = 3$.

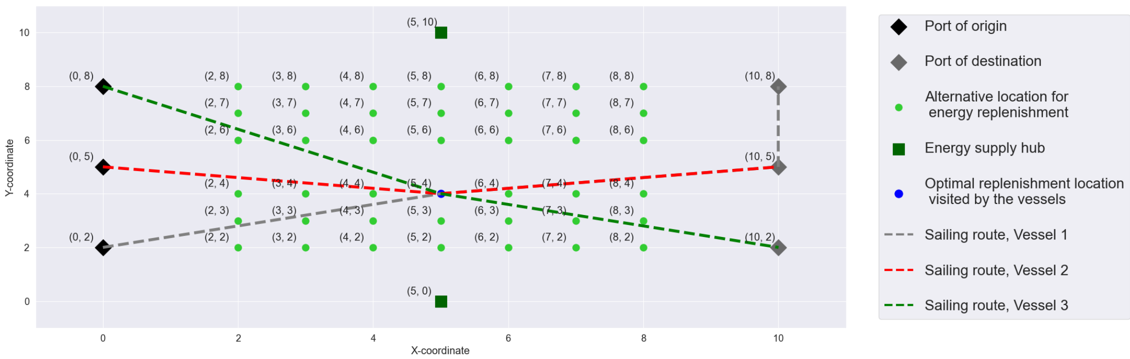


Figure 6.11: Extended model 2 results, $C^{FHS} = 4$.

Test results

The test results for the third node environment are summarized in table 6.6:

Table 6.6: Extended model 3 results.

Vessel number, v	C^{FHS}	**Sailed route**	**Resulting** k^{ES}
1	1	$(0,2),(2,4),(4,4),(6,4),(8,4),(10,5),(10,8)$	6.00
1	2	$(0,2),(2,6),(5,6),(8,6),(10,8)$	8.944
1	3	$(0,2),(2,6),(6,6),(10,8)$	8.944
1	4	$(0,2),(5,4),(10,5),(10,8)$	10.770
2	1	$(0,5),(2,4),(4,4),(6,4),(8,4),(10,5)$	4.472
2	2	$(0,5),(2,6),(5,6),(8,6),(10,5)$	6.00
2	3	$(0,5),(2,6),(6,6),(10,5)$	8.246
2	4	$(0,5),(5,4),(10,5)$	10.198
3	1	$(0,8),(2,6),(4,4),(6,4),(8,4),(10,2)$	5.656
3	2	$(0,8),(2,6),(5,6),(8,6),(10,5),(10,2)$	6.00
3	3	$(0,8),(2,6),(6,6),(10,5),(10,2)$	8.246
3	4	$(0,8),(5,4),(10,2)$	12.806

Figures 6.8 - 6.11 display how the model identifies optimal energy replenishment locations in the model's network of 42 locations and connecting arcs for each of the three vessels. Four tests are run for the new node environment, each with a different C^{FHS} value.

The model generates five optimal locations when C^{FHS} is 1. At the same time, it is clear that each vessel visits only four locations in the optimal solution. This is because the fuel hub in $(5,0)$ services four locations, whereas the fuel hub in $(5,10)$ only services one location. Allowing C^{FHS} to equal 2 reduces the optimal locations to three. All vessels visit each optimal replenishment location because the fuel hub in $(5,10)$ services all optimal locations discovered. The same is true for the third test, in which C^{FHS} takes the value of 3 and discovers two optimal locations serviced by the fuel hub in $(5,10)$. C^{FHS} is set to 4 in the final test run, resulting in only one optimal replenishment location. The optimal location, as seen, is serviced by the fuel hub in $(5,10)$ and is visited by all three vessels.

As with previous scenarios, an increase in C^{FHS} leads to fewer optimal locations for energy replenishment and, as a result, an increase in the vessel's energy storage capacity. These findings reinforce the model's validity even more.

6.4.4 Node environment 4 - 64 alternative replenishment locations

The final node environment investigated consists of 63 alternative locations as illustrated in figure 6.2d. Each fuel hub now serves 31 and 32 locations, respectively, and forms a grid of alternative locations for energy replenishment between the ports and the fuel hubs. The final node environment will be investigated using test parameters presented in Table 6.7a.

(a) Extended model 4, test parameters.

Parameter	Value
C^S	3
C^{LOC}	6
C^{FHS}	**1** / **2** / **4**
C^{RLE}	1
K^V	30
E^V	2

(b) Coordinates for the port of origin and port of destination.

Vessel number, v	O_v coordinate	D_v coordinate
1	$(0, 2)$	$(10, 8)$
2	$(0, 5)$	$(10, 5)$
3	$(0, 8)$	$(10, 2)$

Table 6.7: Input data for the extended model, node environment 4.

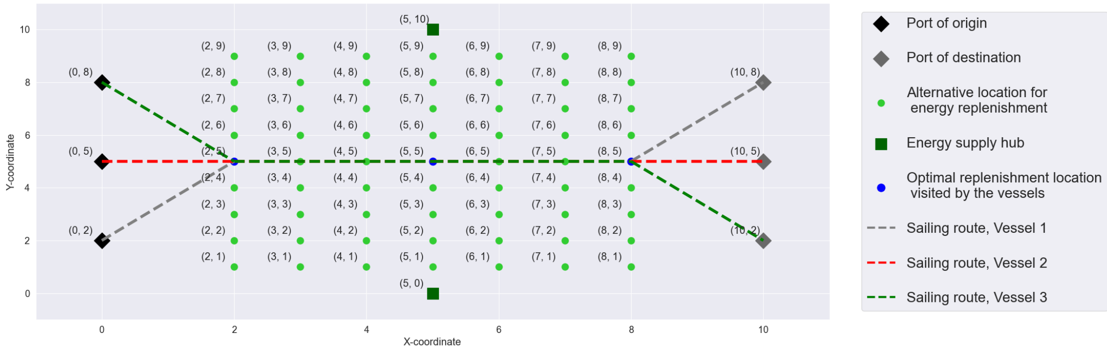


Figure 6.12: Extended model 4 results, $C^{FHS} = 1$.

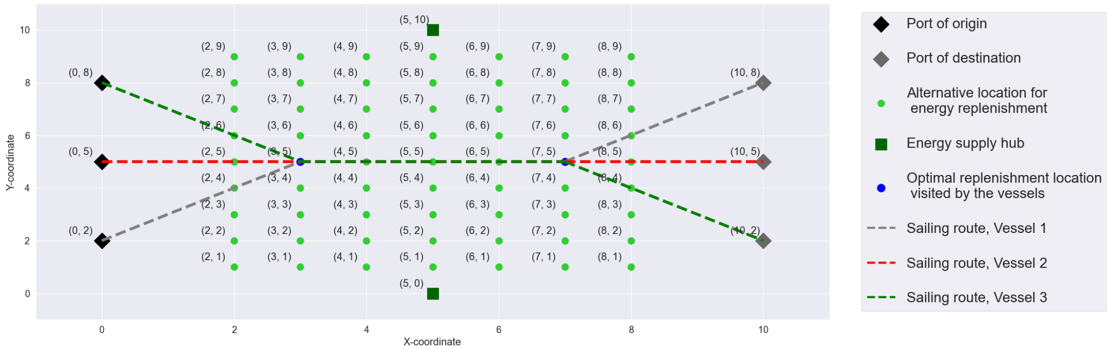


Figure 6.13: Extended model 4 results, $C^{FHS} = 2$.

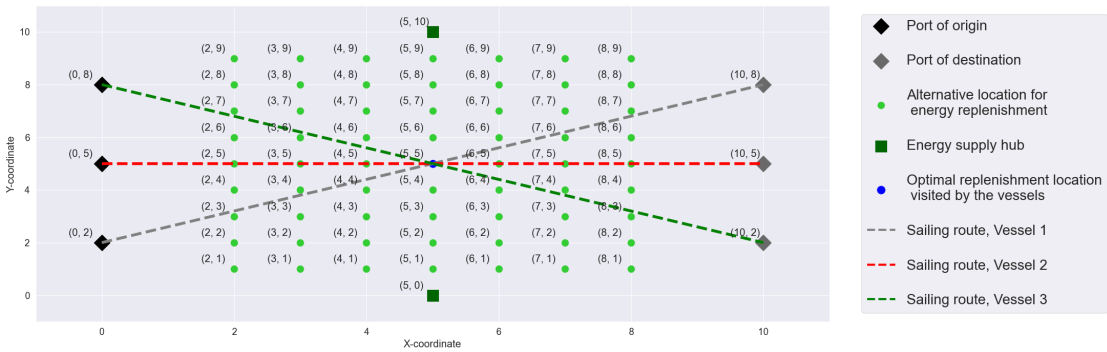


Figure 6.14: Extended model 4 results, $C^{FHS} = 4$.

Test results

The test results for the fourth and final node environment are summarized in Table 6.8:

Table 6.8: Extended model 4 results.

Vessel number, v	C^{FHS}	**Sailed route**	**Resulting** k^{ES}
1	1	$(0,2),(2,5),(5,5),(8,5),(10,8)$	7.211
1	2	$(0,2),(3,5),(7,5),(10,8)$	8.485
1	4	$(0,2),(5,5),(10,8)$	11.661
2	1	$(0,5),(2,5),(5,5),(8,5),(10,5)$	6.00
2	2	$(0,5),(3,5),(7,5),(10,5)$	8.00
2	4	$(0,5),(5,5),(10,5)$	10.00
3	1	$(0,8),2,5),(5,5),(8,5),(10,2)$	7.211
3	2	$(0,8),(3,5),(7,5),(10,2)$	8.485
3	4	$(0,8),(5,5),(10,2)$	11.661

As seen in Figures 6.12, 6.13, and 6.14, the model can also handle the final node environment of 63 alternative locations for energy replenishment. When the CFHS takes the value 1, three optimal locations are established through the horizontal centerline in the coordinate system.

Furthermore, when C^{FHS} increases to 2 and 4, the optimal locations remain along this line but move closer to the energy hubs. As it stands from the test results, each of the optimal solutions presented identifies optimal locations that are equally distant from the two fuel hubs. This implies that even though each replenishment location allocates to a specific fuel hub, it makes no difference which fuel hubs service which location as long as there is enough fuel in the fuel hubs.

In this scenario, the vessel's energy storage capacity will increase as the number of optimal locations for energy replenishment decreases because the vessels will need to sail longer distances between each node. After thoroughly testing the model presented in Chapter 6.3 in four different node environments, it is possible to conclude that the extended model provides a sufficient foundation for further investigation and application in a more specific case study.

Chapter 7

Case study: Optimal location for energy replenishment on Northeast Asia - US green corridor

Until now, the model presented in this master's thesis has been thoroughly tested and validated on a general basis with arbitrary values in order to understand the model's basic structures and principles. However, such a model will not necessarily represent a real-world scenario. For that reason, applying the model developed on a realistic case, i.e., a green corridor with the necessary extensions that best simulate a real-world scenario, will be advantageous.

The optimization model presented in chapters 5 and 6 will be the foundation for the extended optimization model utilized in the following case study. Moreover, we introduce a proposed green shipping corridor, the North East Asia-US Pure car carrier route, which will serve as the basis for the analysis. A deep dive into the corridor's most critical aspects and components are performed. Moreover, the study aims to investigate and locate optimal locations for energy replenishment for alternative-fueled PCC vessels traveling along the route. As with previous models, *Gurobi Optimization*, in combination with Python, will be the tool of choice for solving and visualizing the results from the case study.

7.1 Corridor to be investigated: Northeast Asia - US Pure Car Carriers

As presented in Chapter 2.1, the industry currently investigates several trade routes to become green shipping corridors. When deciding which routes to develop, it is vital to investigate the shipping impact of the selected route. Evaluating the shipping impact of a trade route can be performed by looking into the completion days and the ton-miles of each voyage. The time interval between the date of arrival at the port of destination and the date of departure in the port of departure determines completion days for a single voyage of a vessel. Furthermore, Ton miles are defined as the total amount of cargo in tons multiplied by the mileage in nautical miles.

Some trading routes will have a higher shipping impact than others. It is typically due to the varying amount of cargo transported and the sailing distances from route to route. Transforming high-impact shipping routes into green corridors will be important as the emission reduction potential is higher on these routes. However, high shipping impact routes will cause more challenges and barriers than lower volume routes. Low-volume shipping routes demonstrating fewer vessels, operators, and customers might, in fact, turn into excellent green corridor alternatives. The transpacific pure car carrier (PCC) corridor is an example of such a route. The route emphasizes the transportation of cars and other rolling cargo on specialized PCC vessels from factories in northeast Asia to the West coast of the United States. Many critical stakeholders on the route are already starting to take action and are committed to decarbonizing their businesses. Such initiatives imply a willingness to collaborate and can strengthen the cross-value chain collaboration across the corridor, which will be vital.

Energy replenishment of alternative fuels could be critical for accelerating the transpacific PCC green corridor. Several PCCs are making Transpacific voyages as a part of their sailing routes.

These legs cover long distances and have limited land areas, resulting in few ports where the vessels can bunker between the two continents. Therefore, PCC vessels are currently running on conventional fuel to have the necessary range to make the transpacific journeys. However, energy replenishment of alternative fuels, offshore or at strategic land-based locations along the trade route, could solve the range issue. It can accelerate the development of alternative-fueled PCC and other vessel segments, which will be a requirement for the success of the green corridor. Figure 7.1 highlights the geographical area of focus.

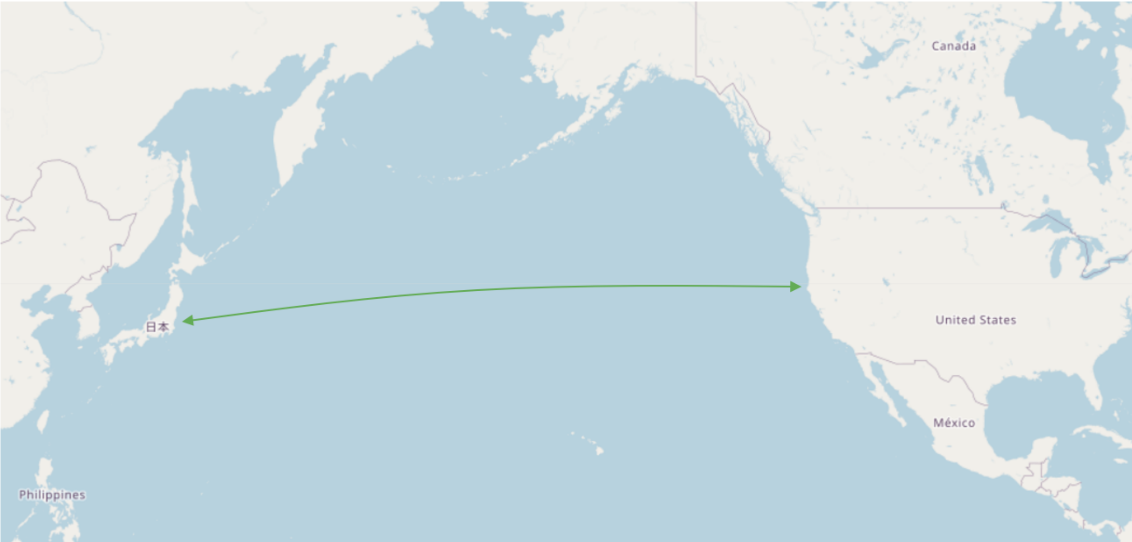


Figure 7.1: Geographical area of the Northeast Asia green corridor.

7.1.1 The Car Carrier Market

Car carriers predominantly operate on liner-style services with regular sailing schedules (i.e., services with fixed frequency and port calls). The operating environment is relatively consolidated, with few operators controlling most of the market. Most of the major vessel operators are typically also owners. However, many businesses also charter in tonnage from charter owners when required (Clarksons Research 2021).

The largest car carrier companies operating in the market control the majority of the market capacity at any given time, either directly or through partially or wholly owned subsidiaries. Northeast Asia is the leading region in the car carrier market, with major liner companies such as NYK, K-Line, MOL, and Hyundai Glovis. Europe follows with operators such as Wallenius Wilhelmsen, Höegh autoliners, and Grimaldi. These companies control 65 % of the total market, including the vast majority of tonnage deployed on the main deep-sea trade lanes, and often have contracts of affreightment (CoAs) with the major car manufacturers (Clarksons Research 2021). Figure 7.2 summarizes the major global car trade routes.

NYK, K-Line, and MOL operate services on major trade routes out of Japan to major import regions, including US and Europe, while Hyundai Glovis is the main operator out of South Korea. Höegh autoliners, Wallenius Wilhelmsen and Eukor, operate a range of services worldwide, from the far east to Europe and North America. Hoegh and K-Line are also running primary trans-Atlantic services. Grimaldi operates a range of services in the Atlantic and the far east. Operators like UECC, Grimaldi, and EML also provide services within Europe, while Wallenius Wilhelmsen, MOL, Eukor, and Shanghai Ansheng operate services within the Pacific basin (Clarksons Research 2021).

At the beginning of November 2021, the global car carrier fleet consisted of a total of 764 vessels comprising a total of 4 million car equivalent units (ceu). 11 vessels of a combined 56 000 ceu was delivered into the sector between January and October 2021, compared to 8 vessels of 55 000 ceu in the full year of 2020. It should also be highlighted that four vessels of a combined 13 000 ceu were scrapped during 2021 compared to 23 ships of 114 000 ceu in 2020.

This was the highest annual total since 2016 and had its explanation in significant market pressure coming into full force in 2020 (Clarksons Research 2021).

In the coming years, the accelerating electrification of the automotive industry is expected to result in a positive development for the sector. As car manufacturers are moving to electric cars, it will be reasonable to assume that transporting cars in a more carbon-neutral way would be a natural extension of their strategies. Green PCC corridors could therefore be an attractive offer for car manufacturers. In addition, several factors likely add support. Electric vehicles are normally heavier and larger than traditionally fueled vehicles, causing an increased shipping demand, new trade flows are emerging, and the accelerating replacement of older vehicles should lend support to both new vehicle sales as well as secondhand vehicle trades (Clarksons Research 2021). Further details of the car carrier market are provided in appendix A.

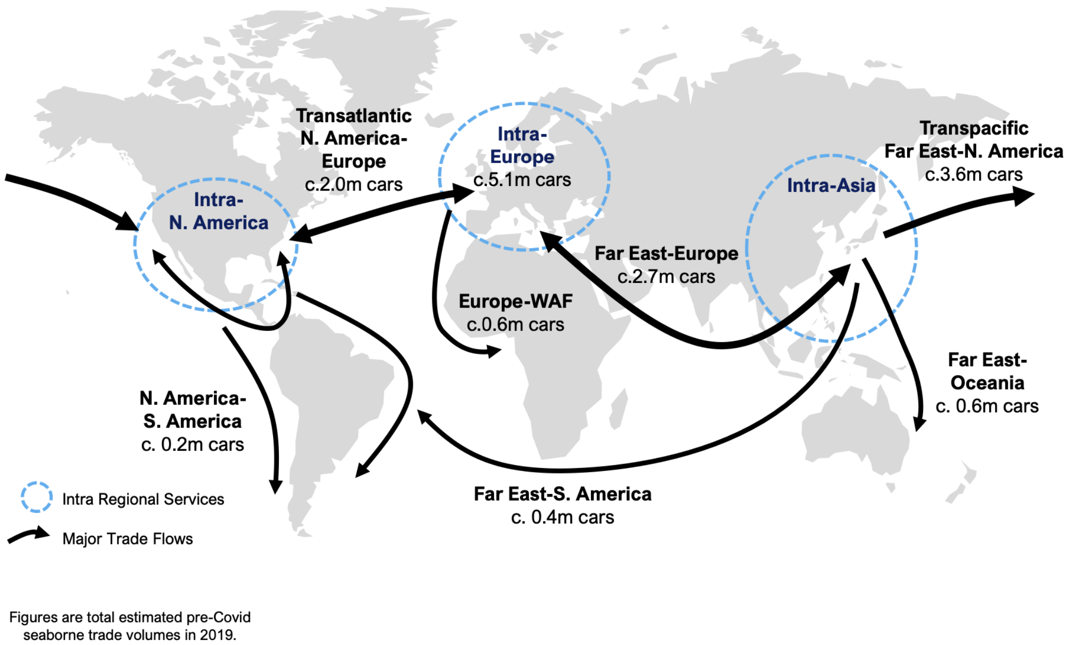


Figure 7.2: Major seaborne car trade routes (Clarksons Research 2021).

7.1.2 Key stakeholders on the corridor

As discussed in 2.5, cross-value chain collaboration between stakeholders is one of the foundational requirements for the success of a green shipping corridor. The following chapter highlights some of the most critical Northeast Asia - US PCC corridor stakeholders that must come together for a successful logistical value chain.

Vessel operator-owners & charter-owners

PCC operators and owners will be natural stakeholders in the corridor. The shipping segment divides between operator owners and charter owners. Operator-owners own and operate their vessels, while charter owners are considered tonnage providers who typically lease their ships to operators. As introduced in Chapter 7.1.1, the shipping segment consists of relatively few companies controlling most of the market. It will be necessary for the success of the green corridor that these companies signalize a willingness to take sustainability actions in their operations, whether it is ordering newbuildings ready for alternative fuels or implementing other technological measures profiting sustainable operations. Fortunately, several prominent players, such as Wallenius Wilhelmsen and Höegh Autoliners, have already started to take action. The new *Aurora class* proposed by Höegh Autoliners will include multi-fuel engines capable of operating on biofuel and conventional fuels, including LNG. The vessel will also be able to transition into zero-carbon fuels such as ammonia by implementing minor modifications (Höegh Autoliners 2021). Wallenius Wilhelmsen is also upfront with its *Orcell wind* concept, a PCC that will use wind as the main form of propulsion. By utilizing sails, the company claims to operate at speeds of 10-12 knots, which can further increase with a supplemental power system (Wallenius Wilhelmsen 2021).

Cargo owners (Car manufacturers)

Cargo owners, i.e., car manufacturers, will also be prominent stakeholders. As described in Chapter 7.1.1, the car industry is moving to an electrification pathway, with more electrical vehicles offered to the market. The car industry's electrification will increase the shipping demand due to heavier cargo and less cargo carrying capacity. Even though transportation and logistics only account for around six percent of the life cycle emissions of automotive vehicles (Hannon et al. 2020). Asian car manufacturers like Toyota, Nissan, Hyundai, and Mazda and transportation and logistics providers must come together to create low-carbon logistical value chains.

Policy and regulatory institutions

Policy and regulatory institutions in Asia and America must be brought to the table to accelerate and realize the Northeast Asia - US PCC green corridor. A cost gap between conventional and zero-emission fuels will likely exist regardless of the available fuels on the corridor. Therefore, policy and regulatory institutions in Asia and North America are vital. They can help reduce the gap and facilitate green fuel production and distribution to vessels operating between the continents. One example of such collaboration is establishing a CFD spanning all countries involved in the corridor. Moreover, it is possible to establish bonded zones spanning all countries involved where no tax is required for importing or distributing alternative fuels such as ammonia or hydrogen. The CFD can extend to include potential alternative fuel production countries such as Australia and Chile.

To succeed, Northeast Asia - US green corridor must at least bring all the above stakeholders to the table. The more stakeholders that come together for collaborative incentives, the better. However, it would make sense to emphasize a couple of additional stakeholders involved in the corridor, and Figure 7.3 summarizes the most important ones.

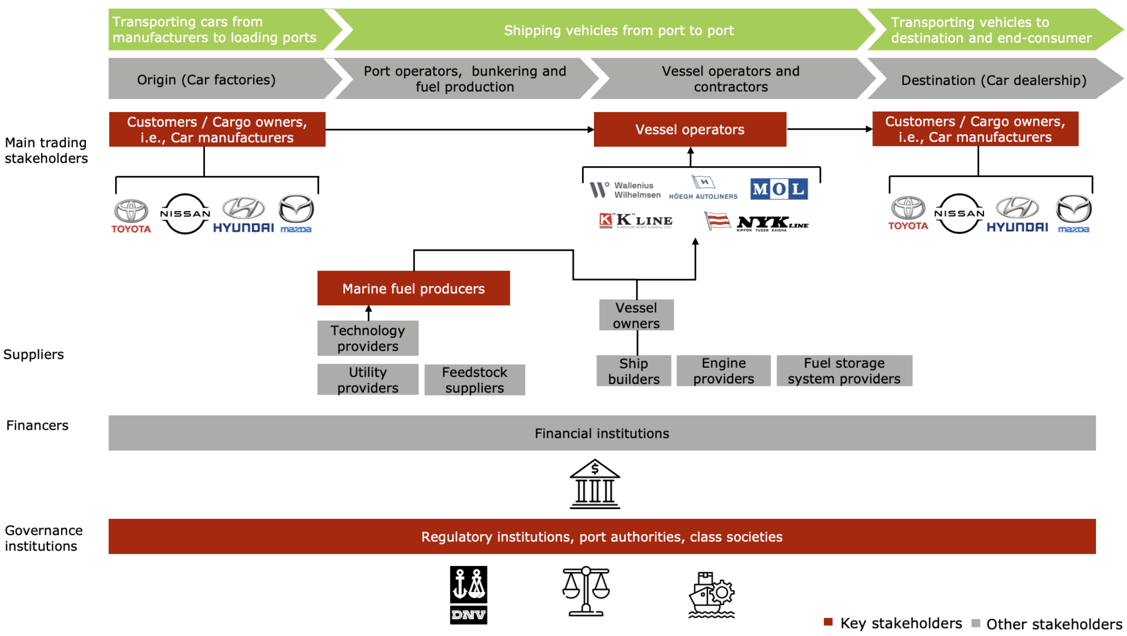


Figure 7.3: Key stakeholders in the PCC green corridor (Developed from Global Maritime Forum et al. 2021).

7.1.3 Ports

Identifying ports will be essential for developing the PCC green corridor. They are important in the logistical value chain and must demonstrate alternative fuel availability and necessary bunkering infrastructure. As PCCs are the vessel segment of choice, selecting ports with high export or import of cars will only be natural. Table 7.1 briefly analyzes typical loading and offloading ports of Asia and America's five biggest PCC companies. The analysis provides decision support for selecting ports in this case study.

Table 7.1: Ports visited by PCCs in Asia and North America.

Company	Loading port	Coordinates (lat/lon)	Offloading port	Coordinates (lat/lon)
Wallenius Wilhelmsen	Singapore	(1.320460, 103.720421)		
	Inchon, South Korea	(37.478090, 126.640290)		
	Masan, South Korea	(35.219100, 128.583560)	Tacoma, USA	(47.52036, -122.38622)
	Kobe, Japan	(34.68892, 135.22750)	Long Beach, USA	(33.7542, -118.2165)
	Nagoya, Japan	(35.03592, 136.79626)	Manzanillo, Panama	(19.053280, -104.316132)
	Yokohama, Japan	(35.61824, 139.98534)		
	Hitachinaka, Japan	(35.686960, 139.749460)		
Höegh Autoliners	Singapore	(1.320460, 103.720421)	Lazaro Cardenas, Mexico	(17.962410, -102.197151)
	Laem Chabang, Thailand	(13.088530, 100.883728)		
	Shanghai, China	(31.21983, 121.48699)		
	Masan, South Korea	(35.219100, 128.583560)		
	Kobe, Japan	(34.68892, 135.22750)		
	Nagoya Japan	(35.03592, 136.79626)		
	Kawasaki, Japan	(35.529991, 139.705002)		
NYK-Line	Yokohama, Japan	(35.61824, 139.98534)	Hueneme, USA	(34.149059, -119.196953)
			Lazaro Cardenas, Mexico	(17.962410, -102.197151)
K-Line	Pyeongtaek, South Korea	(37.568290, 126.997780)	Hueneme, USA	(34.149059, -119.196953)
	Yokohama, Japan	(35.61824, 139.98534)	Lazaro Cardenas, Mexico	(17.962410, -102.197151)
Glovis	Pyeongtaek, South Korea	(37.568290, 126.997780)	New Westminister, British Colombia	(49.219610, -122.908460)
			Tacoma, USA	(47.52036, -122.38622)
			Hueneme, USA	(34.149059, -119.196953)

As seen in Table 7.1, there are significantly more port calls in Asia compared to America. Additionally, Japan and South Korea are the most visited countries for the loading of cars, and several ports in Japan and South Korea are regulars for many of the biggest PCC companies, including Yokohama, Kobe, Nagoya, Masan, and Pyeongtaek, to name a few. It is unsurprising, as all these ports rank within the top five busiest ports in Japan and South Korea concerning car export. Nagoya is considered the home of the Japanese automotive industry, with approximately 1.4 million completed automobiles shipped annually (iContainers 2023). Similarly, Pyeongtaek is the largest port for exporting finished vehicles in South Korea (Ludwig 2015). Although only a few major PCC companies currently make port calls in China, the country and its strategic ports should be emphasized, as they might become critical in a future green corridor scenario. In recent years, China has seen significant growth in both the export and import of cars to the country, mainly due to the substantial growth of Chinese-produced electrical vehicles entering the world's car market. Shanghai is currently the leading port for the country's export and import of cars, and it might turn into a central port on the PCC corridor.

On the other side of the corridor, i.e., in North America, one will find several ports that receive cars from Asia. Table 7.1 shows that ports such as Tacoma and Hueneme are standard ports in the US visited by PCCs. However, the ports of San Diego, Portland, Long Beach, Los Angeles, and Vancouver should all be highlighted as they form the list of the top US west coast vehicle handling ports. Moreover, the port of Lazaro Cardenas in Mexico could be critical as it is a commonly visited port in North America. Additionally, its strategic location near the Panama Canal makes it a natural stop for those PCC vessels continuing their voyage into the Caribbean Sea and the

Gulf of Mexico. Considering the initial port analysis, six ports are selected for the case study. Table 7.2 summarizes the selected ports.

Table 7.2: Selected ports for the case study

Port	**Country**	**Coordinates (lat/lon)**
Nagoya	Japan	$(35.03592, 136.79626)$
Pyeongtaek	South Korea	$(37.568290, 126.997780)$
Shanghai	China	$(31.33602, 121.64334)$
Tacoma	USA	$(47.52036, -122.38622)$
Hueneme	USA	$(34.149059, -119.196953)$
Portland	USA	$(45.64422, -122.7515)$

7.1.4 Fuel hubs

In addition to the ports, this case study investigates the possibility of establishing dedicated fuel hubs in the corridor. Fuel hubs could, in addition to the ports, be a critical component as they will enable additional options for refueling beyond the proposed ports. The hubs can serve as fuel hubs, producing and distributing fuel to other replenishment locations in the network, but also as a location for energy replenishment. It is, therefore, critical that such hubs hold a strategic location between the two continents and a relatively close distance to other intended replenishment locations in the network. As discussed in Chapter 3.6, numerous offshore energy replenishment concepts are under investigation, and some can serve as both offshore fuel production and replenishment facilities. These concepts could be competitive alternatives to the fuel hubs. In this case study, however, we propose a solution where the fuel hubs serve as land-based fuel production facilities where dedicated bunkering vessels operate out from the fuel hub and services specific offshore locations in the pacific ocean by STS-bunkering operations.

For the transpacific Northeast Asia US corridor, strategically locating land-based fuel hubs can be challenging as the corridor primarily consists of the pacific ocean. However, two options are available. By looking at the geographical area of the corridor, as illustrated in Figure 7.1, the Hawaiian Islands could be a location for establishing a fuel hub. The Hawaiian Islands are a vital transportation and communication center in the middle of the Pacific Ocean and are considered the link to the Pacific Rim economies (State of Hawaii, Department of Transportation 2012). Ten commercial harbors exist on the islands, with Honolulu Harbor being the most prominent and busiest port.

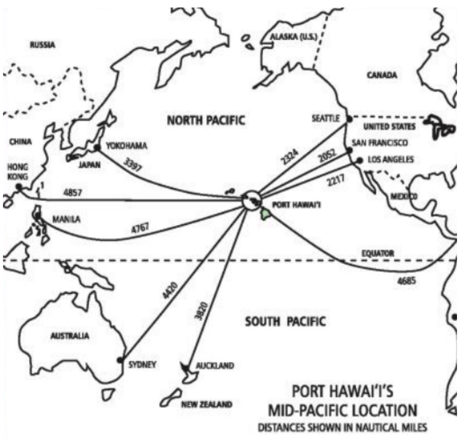


Figure 7.4: Hawaii's strategic geographical location in the Pacific Ocean (State of Hawaii, Department of Transportation 2012).

In addition to the Hawaiian Islands, the Aleutian Islands are proposed as an additional location for a fuel hub. This chain of small islands separates the Bearing Sea from the central portion of the Pacific Ocean. Most of the Islands are a part of the U.S. state of Alaska and are inhabited by natives called Unangan (Encyclopedia Britannica 2023). The economy of the Aleutian Islands is mainly centered around fishing, which means there needs to be more port infrastructure on the islands suitable for bigger vessels. Nevertheless, the International Port of Dutch Harbour in Unalaska could be suitable for establishing a secondary fuel hub on the corridor. Unalaska is the epicenter for commercial fishing in the Bearing Sea and the home of the westernmost container terminal in the United States (City of Unalaska 2023). Such characteristics indicate that the area can handle larger PCC ships as they already demonstrate success with container vessels. At the same time, it would be reasonable to assume that the area must develop the necessary infrastructure to establish a fuel hub capable of producing and distributing fuels.

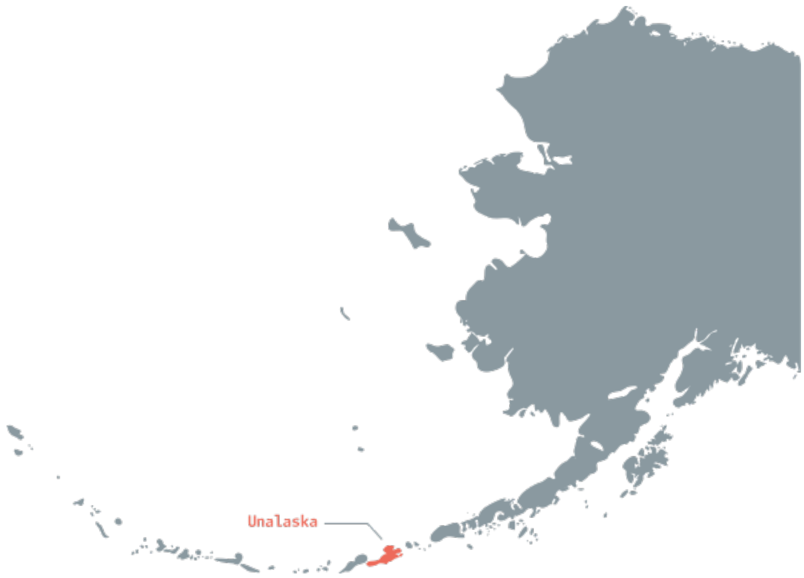


Figure 7.5: Geographical location of Dutch Harbour, Unalaska (Moran 2017).

7.1.5 Offshore replenishment locations

The pacific ocean is a central part of the Northeast Asia-Us corridor. It covers enormous sea areas with limited land between the continents, implying limited access to ports where energy replenishment occurs. As introduced in Chapter 7.1.4, Dutch Harbour and Hawaii could serve as optional land-based locations for energy replenishment in an Asian, US, green corridor. However, these locations might not be optimal for a PCC vessel making the transpacific journey. Offshore energy replenishment as an additional option to the fuel hubs may result in a more efficient and optimal sailing route for the vessels. The main concern with offshore energy replenishment is where to establish the replenishment locations. In reality, offshore energy replenishment can occur at any geographical location in the Pacific Ocean. To simulate such circumstances, generating an n-by-n grid of replenishment locations covering the whole geographical sea area is a reasonable option. However, such a strategy will likely induce a complex network with many nodes that may be challenging to solve from an implementation point of view. Therefore, this thesis proposes an alternative solution.

Our solution involves setting up a replenishment network for PCC vessels in the Pacific Ocean, consisting of two smaller grids that offer energy replenishment. These grids cover a suitable area within the corridor and connect to the proposed fuel hubs through bunker vessels. These bunker vessels operate from the fuel hubs and meet the PCC vessels at the optional locations for a ship-to-ship STS bunkering operation. However, this is only valid if the offshore location is part of the optimal solution. Moreover, the offshore locations are modeled as a four-by-four grid, each having three latitudes and longitude coordinates apart from each other.

Based on the preliminary geographical analysis of strategic locations on the corridor, this thesis proposes two land-based fuel hubs and 24 optional offshore locations. The locations and their respective geographical coordinates are further summarized in Table 7.3 and are visually displayed in Figure 7.6.

Table 7.3: Optional locations for energy replenishment between Northeast Asia and the US west coast (RL = replenishment location).

Location	**Region**	**Type**	**Coordinates (lat/lon)**
Dutch Harbour, Unalaska	USA	Fuel hub & RL	$(54.13784, -166.51691)$
RL1	Pacific Ocean	RL	$(50, -155)$
RL2	Pacific Ocean	RL	$(50, -150)$
RL3	Pacific Ocean	RL	$(50, -145)$
RL4	Pacific Ocean	RL	$(50, -140)$
RL5	Pacific Ocean	RL	$(45, -155)$
RL6	Pacific Ocean	RL	$(45, -150)$
RL7	Pacific Ocean	RL	$(45, -145)$
RL8	Pacific Ocean	RL	$(45, -140)$
RL9	Pacific Ocean	RL	$(40, -155)$
RL10	Pacific Ocean	RL	$(40, -150)$
RL11	Pacific Ocean	RL	$(40, -145)$
RL12	Pacific Ocean	RL	$(40, -140)$
Honolulu, Hawaii	USA	Fuel hub & RL	$(21.30937, -157.87263)$
RL13	Pacific Ocean	RL	$(35, -195)$
RL14	Pacific Ocean	RL	$(35, -190)$
RL15	Pacific Ocean	RL	$(35, -185)$
RL16	Pacific Ocean	RL	$(35, -180)$
RL17	Pacific Ocean	RL	$(30, -195)$
RL18	Pacific Ocean	RL	$(30, -190)$
RL19	Pacific Ocean	RL	$(30, -185)$
RL20	Pacific Ocean	RL	$(30, -180)$
RL21	Pacific Ocean	RL	$(25, -195)$
RL22	Pacific Ocean	RL	$(25, -190)$
RL23	Pacific Ocean	RL	$(25, -195)$
RL24	Pacific Ocean	RL	$(25, -180)$

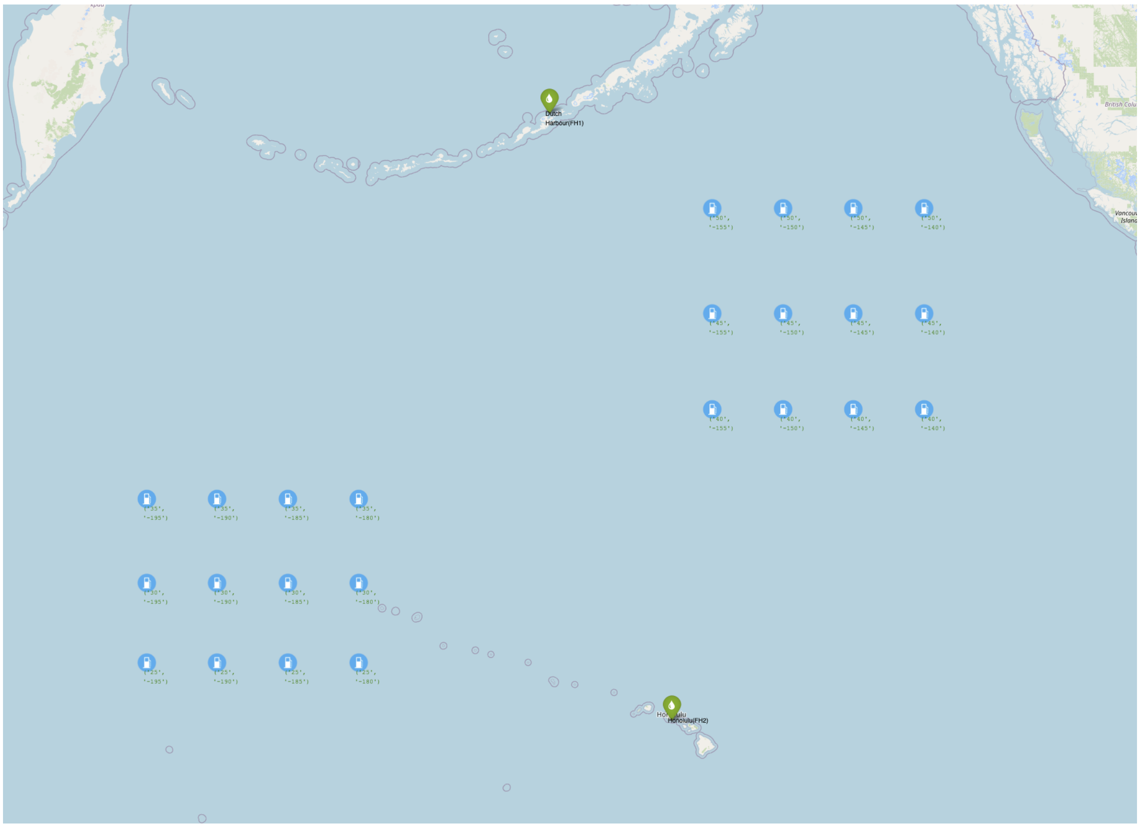


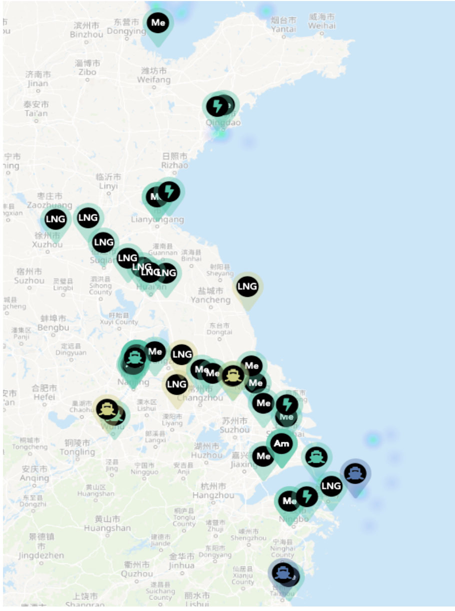
Figure 7.6: Optional offshore replenishment locations on the corridor.

7.1.6 Alternative fuels on the corridor

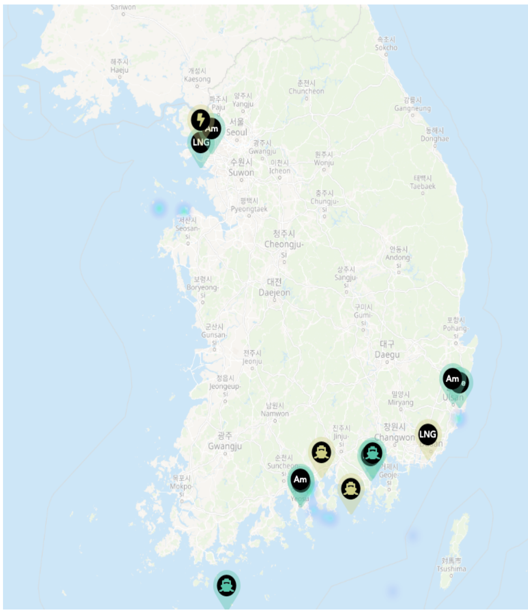
Deciding on an alternative fuel to underline in the corridor is a difficult task, mainly because there might not be one particular alternative fuel that will dominate. As discussed in Chapter 3.4, the shipping industry can emphasize numerous alternative fuels and fuel pathways. However, there is currently no clear winner among the alternatives. Introducing a new fuel into a corridor will require several prerequisites, including the availability of adequate production and distribution facilities, as well as sufficient bunkering infrastructure. Monitoring the uptake of alternative fuels will thus be critical for ship owners and other corridor stakeholders, as it will provide them with helpful information that will allow them to identify the most suitable option for their vessels (DNV 2023b). However, such a task can take time to obtain in practice.

Several recognized stakeholders have begun to take measures to support the shipping industry's transition to a cleaner and greener future by increasing the use of alternative- and low-carbon fuels. One of them is the international class society DNV. DNV created the Alternative Fuel Insight (AFI) platform to help shipowners and other stakeholders track the global adoption of alternative fuels. Central for the platform is to improve clarity for various stakeholders, allowing them to make informed decisions. It will assist shipowners in selecting fuel for the vessels they order today and in the coming years and fuel suppliers in weighing up investments in new bunkering infrastructure. The platform will also benefit maritime authorities by increasing transparency, while equipment suppliers can gather intelligence for product development strategies (DNV 2023b). For these reasons, the AFI platform will be a basis for analyzing and selecting the fuel of choice in this case study.

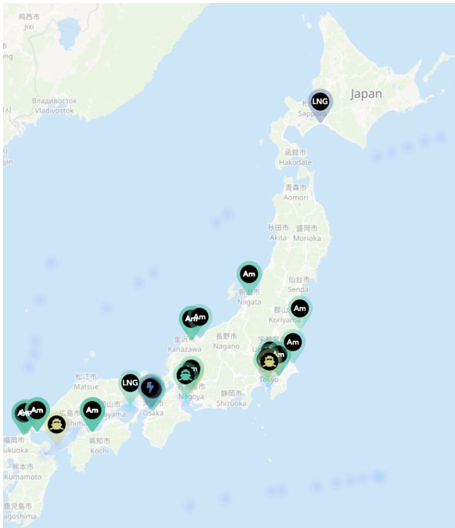
The current alternative fuel availability in the geographical areas included in Northeast Asia - US PCC corridor is investigated by accessing the AFI platform. Figure 7.6 Highlights the current status of alternative fuel infrastructure available on the Northeast Asia - US corridor. High-resolution maps are also provided in Appendix B.



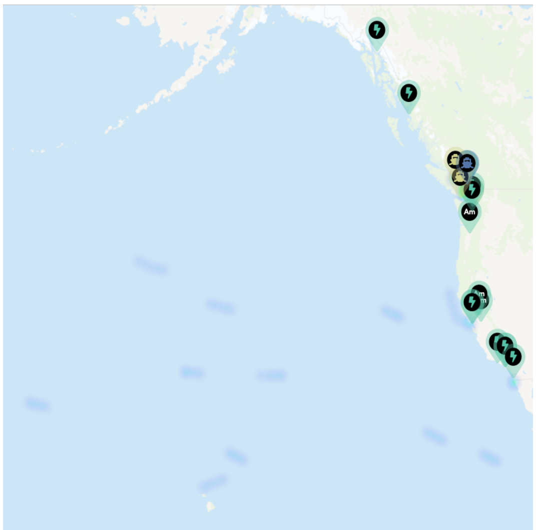
(a) Alternative fuel availability in China.



(b) Alternative fuel availability in South Korea.



(c) Alternative fuel availability Japan.



(d) Alternative fuel availability on the US west coast.

Figure 7.6: Current alternative fuel availability on the Northeast Asia - US corridor (DNV 2023b).

The corridor has infrastructure for several alternative fuels, as shown in Figure 7.6. However, further research into each country is necessary before deciding the fuel to emphasize. Regarding infrastructure, LNG and methanol are expected to be the most promising alternative fuels in China, according to Figure 7.6a. Multiple LNG and methanol terminals with storage and TTS-bunkering infrastructure are currently available in this region. It is also worth noting that there is currently only one ammonia terminal in operation, with a total storage capacity of 34130 tonnes. The terminal is located close to Shanghai, a major port city in Asia. Moreover, Figure 7.6b captures South Korea's current uptake of alternative fuels. LNG and ammonia infrastructure located along the country's coastlines currently dominates. Ammonia storage infrastructure is available in the major port city of Incheon, Yeosu, and Ulsan, and LNG is available through local storage and truck-loading infrastructure. In Japan, ammonia is the preferred alternative fuel. Figure 7.6c shows that ammonia infrastructure is accessible nationwide. However, the current infrastructure concentrates on small-scale local storage, implying that new infrastructure for vessel bunkering will be required. Ammonia is also an alternative fuel demonstrating available infrastructure on the United States west coast. However, local storage is currently the only type of infrastructure available in this region, indicating that new infrastructure supporting ship bunkering will be required in this region as well. Also noteworthy is the need for alternative fuel infrastructure in the areas housing the fuel hubs, namely Alaska and Hawaii. A realistic case study scenario will necessitate fuel infrastructure development in these two regions. Based on the short alternative fuel analysis, ammonia tends to be the most promising fuel on Northeast Asia - US PCC green corridor and will therefore serve as the preferred fuel for further investigation.

Fuel price

Another important aspect of this study is the price of alternative fuels on the corridor, which in this study will be the price of ammonia. In general, estimating and comparing prices for alternative fuels takes much work. Energy content in the fuels will vary significantly, prices may be referred to per Gross Calorific Value, and there are varying standards concerning energy versus quantity and currencies across different markets (DNV 2023b). In this case study, the price estimates of ammonia will be determined based on data obtained from Argus, a leading independent price reporting agency published through the DNV AFI platform. Argus publishes alternative marine fuel prices in three energy equivalents: VLSFOe, MGOe, and British thermal unit (mmBtu). Measuring fuel prices through these energy equivalents allows a fair price comparison based on energy density across alternative marine fuel price suites and conventional marine fuels (DNV 2023b). The current price estimates of ammonia in America and East Asia, measured in energy equivalents, are summarized in Table 7.4.

Table 7.4: Fuel price estimates from DNV AFI.

Region	Fuel type	Price	Unit
East Asia	ammonia	1439	$/t MGOe
East Asia	ammonia	1439	$/t VLFSOe
East Asia	**Ammonia**	**35**	**$/mmBtu**
US	ammonia	1389	$/t MGOe
US	ammonia	1291	$/t VLFSOe
US	**ammonia**	**32**	**$ /mmBtu**

As seen in Table 7.4, the DNV AFI platform emphasizes the price of ammonia through different energy equivalents. Such a strategy has advantages, but converting the price unit to a slightly more relatable unit, such as, e.g., dollar per tonne, would be desirable. For that reason, the dollar per mmBtu energy equivalent unit is utilized to estimate the price of ammonia in dollars per tonne. mmBtu is a unit traditionally used to measure heat content or energy value. However, it can be employed to determine the price of ammonia using the following approach:

Firstly the energy in mmBtu is converted to megajoules using the following equation:

$$megajoule = mmBtu * 1055.055 = 1 * 1055.055 \tag{7.1}$$

Equation 7.1 implies that one mmBtu equals 1055.055853 MJ. This value is then utilized to calculate the energy equivalent of one tonne of ammonia to $mmBtu/tonnes$ by using the specific energy of ammonia:

$$1\,tonn\,ammonia = \frac{18800\,\frac{MJ}{tonn}}{1055.056\,\frac{MJ}{mmBtu}} = 17.819\,\left[\frac{mmBtu}{ton}\right] \tag{7.2}$$

Furthermore, the value obtained in equation 7.2 are utilized in combination with the highlighted prices from table 7.4 to estimate the price of ammonia in $\$/ton$:

$$1\,tonn\,ammonia\,(East\ Asia) = 17.819\,\frac{mmBtu}{ton} \cdot 35.00\,\frac{\$}{mmBtu} = 623.7\,\left[\frac{\$}{ton}\right] \tag{7.3}$$

$$1\,tonn\,ammonia\,(US) = 17.819\,\frac{mmBtu}{tonn} \cdot 32.00\,\frac{\$}{mmBtu} = 570.2\,\left[\frac{\$}{ton}\right] \tag{7.4}$$

Finally, the price of ammonia in each region is converted to $\$/m^3$ by multiplying the price in $\$/ton$ with the density of liquid ammonia which is equal to 0.82335 ton/m^3 at 15 degrees Celsius:

$$623.665\,\frac{\$}{ton} \cdot 0.6170\,\frac{ton}{m^3} = 384.8\,\left[\frac{\$}{m^3}\right] \tag{7.5}$$

$$570.208\,\frac{\$}{ton} \cdot 0.6170\,\frac{ton}{m^3} = 351.8\,\left[\frac{\$}{m^3}\right] \tag{7.6}$$

By applying the procedure described through equation (7.1) to (7.4), the final estimates for the price of ammonia which will be utilized in this study, are summarized in Table 7.5.

Table 7.5: Calculated fuel price estimates.

Region	**Fuel type**	**Price**	**Unit**
East Asia	ammonia	384.8	$\$/m^3$
US	ammonia	351.8	$\$/m^3$

7.1.7 PCC vessel characteristics

Examining some critical characteristics of the PCC vessels will be necessary to better illustrate a realistic scenario. PCCs are built in different sizes resulting in distinct vessel characteristics. Energy consumption, storage systems, charter rates, and vessel speed are central to the vessel segment and should be carefully investigated. As discussed in Chapter 7.1.6, ammonia is the most promising fuel on the corridor, and it would be reasonable to investigate ammonia-powered vessels further. However, ammonia-powered vessels have yet to demonstrate success, and ammonia as a fuel for shipping is still an area of research. For these reasons, it will only be natural to make suitable assumptions in this case study, especially concerning fuel consumption at different speeds. The following chapter summarizes the most significant characteristics of the PCC vessels. It shall serve as decision support for input data to the optimization model presented later in the study.

Charter- and freight rates

Charter and freight rates are essential characteristics of commercial vessels, and PCC is no exemption. Regardless of the contract obtained, securing sufficient charter contracts for charterers and shipowners is essential, as it will affect the companies' revenue and contribute to the financial performance. The PCC charter market has developed to the most robust levels seen in over a decade during the past two years after a relatively slow growth since the global financial crisis and the covid-19 pandemic in 2020 (Clarksons Research 2021). Vessel operators report significantly improved earnings due to increased volumes and limited available tonnage capacity.

By the end of 2021, the average time-charter rate for a 6500 ceu PCC vessel was 34 000 $\$/day$ and 25 000 $\$/day$ for a 5000 ceu vessel. Since then, the market has exploded, with rates up to 110 000 $\$/day$ during 2022 (Clarksons Research 2021; Gram Car Carriers ASA 2023a). The market is nevertheless expected to moderate closer to 2021 levels in the coming years but remains at solid levels. With these considerations in mind, Table 7.6 presents expected charter rate estimates for several PCC vessel sizes.

Table 7.6: Estimated PCC charter rates.

Vessel type	**Size [ceu]**	**Charter rate [$ / day]**
PCC/PCTC	5 000	30 000
PCC/PCTC	6 500	40 000
PCC/PCTC	7 500	50 000

Onboard energy storage and conversion systems

Storage and conversion of ammonia onboard the PCC vessels are crucial components that will affect the need for energy replenishment on the corridor and, potentially, the cargo-carrying capacity of the vessels. Fuel cell technology might be applicable for use with ammonia onboard the vessels in a long-term perspective. However, challenges and research and development needs are currently required for the success of such an option. Hence, using ammonia through ICEs, and fuel storage tanks is the most promising option for PCC vessels. ICEs are efficient and robust energy converters for various fuels, and multiple variants and designs currently exist. Since ammonia is stored in either gas or liquid form, it can be utilized as an energy carrier in several different machinery concepts. Research into ammonia as fuel is ongoing on two-stroke and four-stroke engine platforms. The most promising options are the four-stroke, medium-speed, dual fuel, lean burn gas engine, the four-stroke, medium speed, spark ignited, lean burn gas engine, and the four-stroke medium-speed, high-pressure, gas diesel engine. Similar concepts can also be developed in a two-stroke configuration (Green Shipping Programme 2021).

Carrying ammonia as fuel happens in the liquid state, and it must either be refrigerated, compressed, or a combination of these two. Developing suitable storage tanks is therefore important. Fully refrigerated storage tanks contain liquid ammonia at -33 degrees Celsius, while fully pressurized tanks require a pressure of 18 bar, corresponding to the ammonia vapor pressure at 45 degrees Celsius (Hammer et al. 2021). Fully refrigerated and semi- or fully pressurized tanks are optional configurations onboard the PCC vessels. However, several safety-related considerations will need to be addressed when deciding on the type of fuel tank to utilize. Firstly venting of tank vapors should be prevented at all times, meaning that the fuel tanks will require a boil-off gas management system unless they are designed for the full vapor pressure of ammonia at ambient temperatures. Secondly, the management of leakage and subsequent emergency venting of fuel gasses shall be considered. Thirdly, the choice of the fuel tank may also impact flexibility regarding compatibility with bunkering facilities concerning pressure and temperature. Ammonia is also corrosive, causing special requirements for materials used in fuel tanks and associated systems (Hammer et al. 2021). For the safe use of ammonia as fuel, the tanks should be strategically located in the hull, protected from external events and away from exposure to ship- and cargo operations.

Energy consumption

Estimating accurate fuel consumption of ammonia-fueled PCC vessels can be challenging and will require important information about the energy converter onboard. Such data are usually not available to the public. In addition, ammonia-fueled energy converters are still an area of research with no commercial availability at this point in time. For these reasons, it is difficult to provide accurate and realistic information about the energy consumption of the vessels. However, sufficient strategies exist to provide acceptable fuel consumption estimates despite the limited testing and research into ammonia as ship fuel.

In this case study, the fuel consumption of the vessels is estimated by first calculating the specific fuel consumption using the lower heating value (LHV) of ammonia and the energy efficiency, η, of an ammonia-fueled ICE:

$$F_{sfc} = \frac{1}{LHV \cdot \eta} \cdot 1000 \qquad \left[\frac{g}{kWh}\right] \tag{7.7}$$

The specific fuel consumption, F_{sfc} is then utilized to calculate the fuel consumption per nautical mile, F_c using equation 7.8:

$$F_c = \frac{P \cdot F_{sfc}}{V} \cdot \frac{1}{1000000} \qquad \left[\frac{ton}{NM}\right] \tag{7.8}$$

After the fuel consumption is calculated, a conversion from ton(register) per nautical mile to cubic meters per nautical mile is performed using the following conversion formula:

$$Volume\ (m^3) = Volume\ (Tonn) \cdot 2.832 \tag{7.9}$$

P determines the engine power output in kW, F_{sfc} is the specific fuel consumption calculated through equation 7.7, and V is the vessel speed given in knots. To estimate the energy consumption of the vessels operating on the corridor, some assumptions must be made. To obtain a sufficient value of F_{sfc}, the efficiency of the ammonia-fueled ICE is required. Such a value is difficult to obtain without experimental research. However, an option is to rely on previous studies on the subject. Several studies have already been conducted on ammonia-fueled engines and their performance. Lhuillier et al. (2019)s study on combustion characteristics of ammonia in a spark-ignition engine indicated an engine efficiency of 0.36 with the engine running on full load on pure ammonia. Similarly, Nadimi et al. (2023) investigated the effects on combustion and performance of the ammonia/diesel dual-fuel compression ignition engine obtaining efficiencies around 0.38 with 100 % ammonia share in the engine. Previous studies can give us a good indication of reasonable efficiency in a conventional ammonia engine. At the same time, it will require more research to say more about the actual efficiency. The energy efficiency used in this thesis is primarily based on the studies mentioned above. Simultaneously, we recognize that it may differ in line with research development within ammonia-driven ICEs. Based on the presented studies, we estimate the energy efficiency of an ammonia-fueled engine to be 0.37. With the efficiency in place, we only need an estimate of the engine's power output to say something specific about the energy consumption of a PCC vessel. Based on existing PCC vessels and newbuilds in the pipeline, a reasonable power output of such a vessel lies around 12 500 kW (Eaton 2023; Gram Car Carriers ASA 2023b).

Based on the analysis above, the fuel consumption of a 6 500 ceu PCC vessel is estimated for an operational speed of 16 knots using the methodology described through equation 7.7 to 7.9. The estimate are summarized in table 7.7.

Table 7.7: Estimated fuel consumption of a 6 500 ceu PCC vessel at 16 knots.

Vessel size	**Speed,** V	**Fuel consumption,** F_c	F_c **converted**
6 500 [ceu]	16 [kn]	0.4060 $[\frac{tonnes}{NM}]$	1.149 $[\frac{m^3}{NM}]$

Lost opportunity cost

PCC vessels utilizing ammonia as fuel will require new designs compared to existing designs in the fleet. As previously discussed, this is especially true for the volume occupied by fuel storage and energy converter systems onboard. Using ammonia as an energy carrier will require more space and volume in the hull compared to conventional fuels, mainly due to the lower volumetric density of the energy carrier. Increasing the volume occupied by fuel storage and machinery systems will likely substitute valuable space for transporting cars and other vehicles, potentially reducing the vessel's income per voyage. The loss of income, which implies increased volume occupied by energy storage, can be modeled as a lost opportunity cost per cubic meter occupied by ammonia storage systems. Estimating such costs is a difficult task. However, we suggest the following approach:

Firstly the average freight rate for transporting one ceu is estimated. This rate may vary depending on the car's volume and transport distance. However, for this case, the average freight rate is based on the transportation of a 12 m^3 station wagon from Japan to Long Beach. With a car volume rate of 12 m^3/ceu and an average freight rate of 1650 $\$/ceu$ for car transportation, the cost of transporting one ceu is estimated to be 2520 $\$/ceu$ (Japanese Car Trade 2021; Quality auto co., LTD 2023).

Then we estimate the volume occupied by ammonia storage components by investigating how much volume ammonia occupies compared to the same volume a car occupies. By dividing the volume of one ceu by the volumetric density of ammonia, it is discovered that one ceu is equivalent to $16.438 m^3/ceu$ of ammonia storage. The lost opportunity cost per cubic meter can then be estimated:

$$C_v^{LOC} = \frac{2520 \ \frac{\$}{ceu}}{16.438 \ \frac{m^3}{ceu}} = 153.3 \left[\frac{\$}{m^3}\right] \tag{7.10}$$

7.2 Model description

Following a more thorough analysis of the corridor in which the most important aspects have been addressed, the focus is to develop a mathematical model to identify the optimal location for ammonia replenishment and the corresponding storage capacity on board the PCC vessels. The following model aims to monitor a real-world scenario where a fleet of homogeneous PCC vessels sails between ports in Northeast Asia and the West Coast of the US with the option of performing energy replenishment at strategic locations between the two continents. The model presented in this chapter is anchored in the one presented in Chapter 6 but includes the necessary extensions to simulate a realistic scenario sufficiently. As for previous models, the main objective is to minimize the total cost, including the total sailing cost, lost opportunity cost due to the amount of space occupied by ammonia storage and connected energy converter systems, the cost of establishing ammonia fuel hubs on the corridor, and the cost of supplying ammonia from the fuel hubs to replenishment locations.

Many of the parameters in the model from Chapter 6 are present in the case study model. However, some new parameters and variables have been added. Firstly, an additional cost parameter, C_i^A is introduced, describing the cost of ammonia in location i. As the corridor mainly includes Northeast Asia and the US, C_i^A will take a value equal to the ammonia price in Northeast Asia or the price in the US, depending on the specific location. Furthermore, there has to be a maximum amount of ammonia that can be delivered in each replenishment location i, resulting in a new parameter K_i^{AR}. Additionally, the ammonia tanks in the PCCs cannot be fully emptied before refueling due to onboard safety. As a result, a safety factor F^{ASM} is introduced, describing a safety margin, accounting for the amount of ammonia left in the tank. Similarly, the ammonia tanks and the energy converter systems will require additional space due to the tanks' insulation and ventilation systems in case of leakage and other hazardous events. For this reason, another safety factor F^{SC} is introduced, accounting for the additional space required for tanks, machinery arrangement, and other related systems.

Three new variables are also introduced. It will be necessary to monitor the amount of ammonia replenished in each location visited by a vessel and the amount of ammonia onboard the vessel when arriving and leaving the locations visited. Hence, the variable q_{iv} is introduced, describing the amount of ammonia replenished in location i for vessel v, i_{iv}^A describing the amount of ammonia onboard vessel v when arriving at location i and i_{iv}^D, describing the amount of ammonia onboard vessel v when departing location i. The model extensions are further illustrated in figure 7.7.

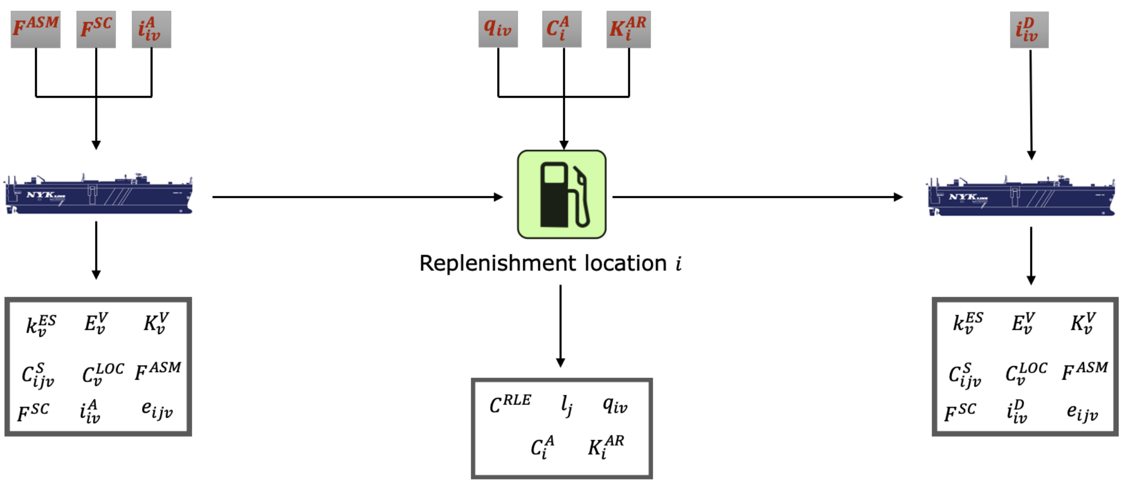


Figure 7.7: Illustrative overview of parameters and variables added to the case study model.

7.3 Model Notation

The following chapter presents sets, parameters, and variables included in the mathematical model.

Sets:

N - Set of Nodes including port of origin for vessel v, O_v and port of destination for vessel v, D_v.

L - Set of energy replenishment locations including the fuel hubs serving node j, H_j, $L \subset N$.

A - Set of arcs between nodes i.

V - Set of vessels v.

Parameters:

C^S_{ijv} - Cost of sailing from node i to j, for vessel v [$\$/NM$].

C^{LOC}_v - Lost opportunity cost per unit ammonia stored in vessel v [$\$/m^3$].

C^{FHS} - Cost of supplying ammonia from the fuel hub per distance unit [$\$/NM$].

C^{RLE} - fixed cost of establishing an ammonia replenishment location [\$].

C^A_i - Cost of ammonia in location i [\$].

K^V_v - Total storage capacity of vessel v [m^3].

E^V_v - Energy consumption per distance unit traveled for vessel v [m^3/NM].

D_{ijv} - Sailing distance between node i and node j for vessel v [NM].

K^{AR}_i - Maximum ammonia delivery capacity in location i [m^3].

F^{ASM} - Factor accounting for the amount of ammonia left in the tank as a safety margin.

F^{SC} - Factor accounting for the additional space required for ammonia tanks, including tank insulation, ventilation, etc.

Variables:

x_{ijv} - $\begin{cases} 1 & \text{if vessel } v \text{ sail from node } i \text{ to } j. \\ 0 & \text{otherwise.} \end{cases}$

l_j - $\begin{cases} 1 & \text{if an energy replenishment location } l \text{ is established in location } j. \\ 0 & \text{otherwise.} \end{cases}$

k^{ES}_v - Energy storage capacity of vessel v [m^3].

e_{ijv} - ammonia consumption from node i to node j for vessel v.

q_{iv} - Amount of ammonia replenished in node i to vessel v.

i^A_{iv} - Amount of ammonia onboard vessel v when arriving location i.

i^D_{iv} - Ammount of ammonia onboard vessel v when departing location i.

7.4 Mathematical model

By utilizing the sets, parameters, and variables defined in 7.3, the following mathematical model is formulated:

$$\begin{aligned}\text{MIN } Z = &\sum_{j\in A}\sum_{v\in V} C^{S}_{ijv} D_{ijv} x_{ijv} + \sum_{v\in V} C^{LOC}_{v} F^{SC} k^{ES}_{v} + \sum_{j\in L/\{H_j\}} \left(C^{FHS} D_{Hjv} + C^{RLE}\right) l_j \\ &+ \sum_{i\in N}\sum_{v\in V} C^{A}_{i} q_{iv}\end{aligned} \tag{7.11}$$

S.t:

$$\sum_{j\in N} x_{O_v jv} - \sum_{j\in N} x_{iO_v v} = 1, \qquad v \in V \tag{7.12}$$

$$\sum_{i\in N} x_{iD_v v} - \sum_{i\in N} x_{D_v iv} = 1, \qquad v \in V \tag{7.13}$$

$$\sum_{j\in L} x_{ijv} = \sum_{j\in L} x_{jiv}, \qquad i \in N, v \in V \tag{7.14}$$

$$\sum_{v\in V} q_{iv} \leq K^{AR}_{i}, \qquad i \in L \tag{7.15}$$

$$q_{iv} \geq 0, \qquad i \in N, v \in V \tag{7.16}$$

$$x_{ijv} + x_{jiv} \leq 1, \qquad (i,j) \in A, v \in V \tag{7.17}$$

$$E^{V}_{v} D_{ijv} x_{ijv} = e_{ijv}, \qquad (i,j) \in A, v \in V \tag{7.18}$$

$$F^{ASM} e_{ijv} \leq k^{ES}_{v}, \qquad (i,j) \in A, v \in V \tag{7.19}$$

$$0 \leq k^{ES}_{v} \leq K^{V}_{v}, \qquad v \in V \tag{7.20}$$

$$x_{ijv} \leq l_j, \qquad i \in N, j \in L, v \in V \tag{7.21}$$

$$i^{D}_{(O_v)v} = k^{ES}_{v}, \qquad v \in V \tag{7.22}$$

$$i^{A}_{(D_v)v} = k^{ES}_{v}, \qquad v \in V \tag{7.23}$$

$$i^{D}_{iv} - e_{ijv} = i^{A}_{jv}, \qquad (i,j) \in N/\{O_v\}, v \in V \tag{7.24}$$

$$q_{iv} = i^{D}_{iv} - i^{A}_{iv}, \qquad i \in L/\{O_v\}, v \in V \tag{7.25}$$

$$0 \leq i^{A}_{iv} \leq k^{ES}_{v}, \qquad i \in N, v \in V \tag{7.26}$$

$$0 \leq i_{iv}^{D} \leq k_{v}^{ES}, \qquad i \in N, v \in V \tag{7.27}$$

$$x_{ijv} \in \{0,1\}, \qquad (i,j) \in A, v \in V \tag{7.28}$$

$$l_j \in \{0,1\}, \qquad j \in L \tag{7.29}$$

The objective function (7.11) is to minimize the total cost, i.e., sailing cost, lost opportunity cost due to ammonia space requirements, cost of establishing ammonia fuel hubs, and cost of supplying fuel from the fuel hubs to the replenishment locations. Constraint (7.12) ensures that exactly one arc can be active from the port of origin for vessel v. Similarly, constraint (7.13) ensures that exactly one arc can be active for the port of destination for vessel v. Constraint (7.14) states that for each energy replenishment location, the sum of inbound arcs must be equal to the sum of outbound arcs. Furthermore, the amount of ammonia supplied to a vessel in a replenishment location cannot exceed the maximum ammonia delivery capacity in the location and is secured through constraint (7.15). In addition, the amount of ammonia replenished in a location cannot be non-negative and is ensured through constraint (7.16). Constraint (7.17) states that only one arc can connect two nodes together for each vessel v. Constraint (7.18) defines the ammonia consumption between two nodes for a vessel. At the same time, constraint (7.19) ensures that the ammonia consumption between two nodes must not exceed the energy storage capacity of the vessel. In addition, the energy storage capacity of vessel v has to be non-negative and cannot exceed the total storage capacity of the vessel. This is secured through constraint (7.20). Constraint (7.21) states that an energy replenishment location is established in a node only if a vessel is visiting the node. Constraints (7.22) and (7.23) state that a vessel is fully loaded with ammonia at the beginning of its voyage and will need to be replenished when arriving at its destination port. Constraint (7.24) states that when a vessel arrives at a node, the amount of ammonia onboard the vessel equals the amount of ammonia the vessel had on board when leaving the previous node minus the energy consumption of the vessel between the two nodes. Constraint (7.25) defines the amount of ammonia that needs to be replenished in a node. This equals the amount of ammonia onboard the vessel when leaving the previous node minus the amount onboard when arriving at the next node. The amount of ammonia onboard the vessel when arriving at a node has to be non-negative and cannot exceed the maximum energy storage capacity of the vessel. This is ensured through constraint (7.26). Similarly, constraint (7.27) ensures that the amount of ammonia onboard the vessel when departing a node has to be non-negative and cannot exceed the maximum energy storage capacity of the vessel. Finally, constraints (7.28) and (7.29) represent binary constraints. The model described in this chapter will be tested and validated using Python and Gurobi optimizer and the results are presented through chapter 8.

Chapter 8

Case study results

The results from the case study described in Chapter 7 are presented in this chapter. Before presenting the results, the objective of this thesis is repeated:

"to provide decision support to stakeholders in green shipping corridors by investigating optimal locations for energy replenishment for zero-emission vessels."

A baseline scenario is first investigated with a given set of input parameters. The model will then be tested through a parameter study and compared to the baseline scenario to see how the model handles various conditions and scenarios.

8.1 Preconditions

Before presenting the results obtained from the parameter study, it is necessary to introduce some preconditions. The preconditions for the results include a fleet of ammonia-fueled 6500 ceu PCC vessels making voyages from loading ports in Northeast Asia to offloading ports on the west coast of the US. Each vessel has a loading port, O_v, and a connecting offloading port, D_v, on the other side of the corridor. Each vessel can be replenished with ammonia at strategic onshore and offshore locations between the continents, as illustrated in Figure 8.1. If an offshore replenishment location is established, and a fuel hub services it, we assume the PCC vessel will be replenished through an STS bunkering procedure by a dedicated bunker vessel operating out of the fuel hub. The bunker vessel's operational pattern is outside this thesis's scope, and it is assumed that the bunkering vessel will be at the optimal location when the PCC vessel arrives.

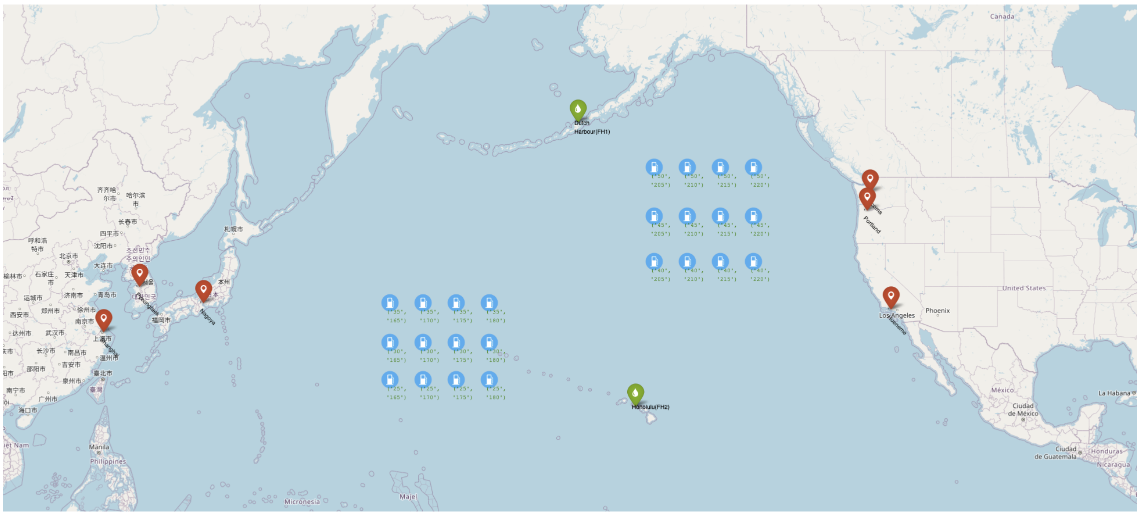


Figure 8.1: Northeast Asia - US replenishment network.

The model described in chapters 7.2, 7.3, and 7.4 is now utilized on the network presented in Figure 8.1 and aims to identify optimal sailing routes on the corridor for every vessel in the fleet while simultaneously estimating the required energy storage capacity and amount of energy supplied in each location visited. The red markers represent the ports, the green markers represent the fuel hubs, and the blue markers are the optional offshore energy replenishment locations. The sailing distances between each of the 32 nodes in the network are provided through a distance matrix in Appendix C. Furthermore, some of the input variables to the model are based on specific calculations, as presented in Chapter 7, while some parameters rely on other research.

8.2 The baseline scenario

The baseline scenario covers nine vessels making the transpacific journey. Table 8.1 presents the selected input parameters, while Figure 8.2 illustrates the optimal routes generated from the model. Moreover, Table 8.2 displays the model results, while Figure 8.3 showcases an illustrative overview of the percentage distribution of the amount of ammonia replenished on each route generated by the model.

Table 8.1: Baseline scenario, input parameters.

Parameter	Value	Unit
C_{ijv}^{S}	160	$[\$/NM]$
C_{v}^{LOC}	153.3	$[\$/m^3]$
C^{FHS}	110	$[\$/NM]$
C^{RLE}	60 000	$[\$]$
C_{i}^{A}	$[351.8, 384.8]$	$[\$/m^3]$
K_{v}^{V}	100 000	$[m^3]$
E_{v}^{V}	1.149	$[m^3/NM]$
K_{i}^{AR}	150 000	$[m^3]$
F^{ASM}	1.38	$[-]$
F^{SC}	1.25	$[-]$

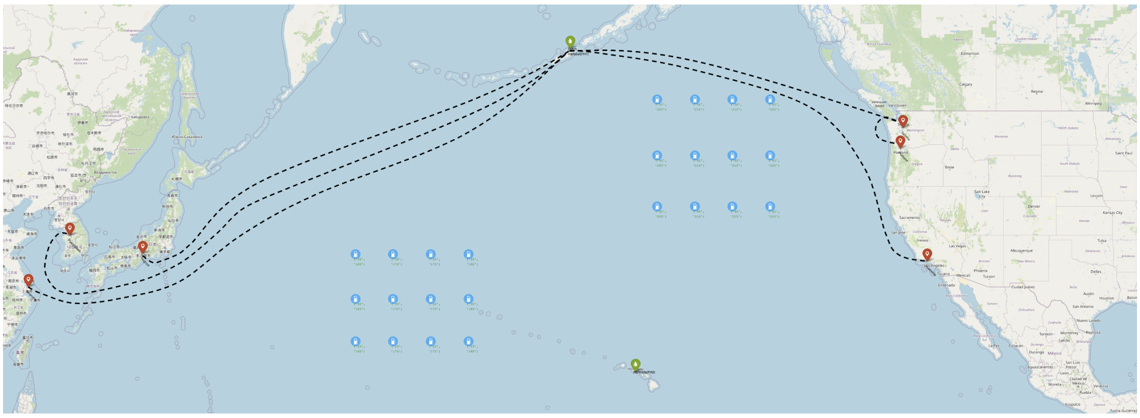


Figure 8.2: Optimal routes for the baseline scenario.

Table 8.2: Model results for the baseline scenario.

Vessel, v	**Optimal route**	**Ammonia replenished on route** $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - Dutch Harbour - Tacoma	5718	5211
2	Shanghai - Dutch Harbour - Tacoma - Portland	5849	5211
3	Shanghai - Dutch Harbour - Hueneme	6424	5211
4	Pyeongtaek - Dutch Harbour - Tacoma	5221	4525
5	Pyeongtaek - Dutch Harbour - Tacoma - Portland	5352	4525
6	Pyeongtaek - Dutch Harbour - Hueneme	5927	4525
7	Nagoya - Dutch Harbour - Tacoma	4924	4115
8	Nagoya - Dutch Harbour - Tacoma - Portland	5054	4115
9	Nagoya - Dutch Harbour - Hueneme	5629	4115

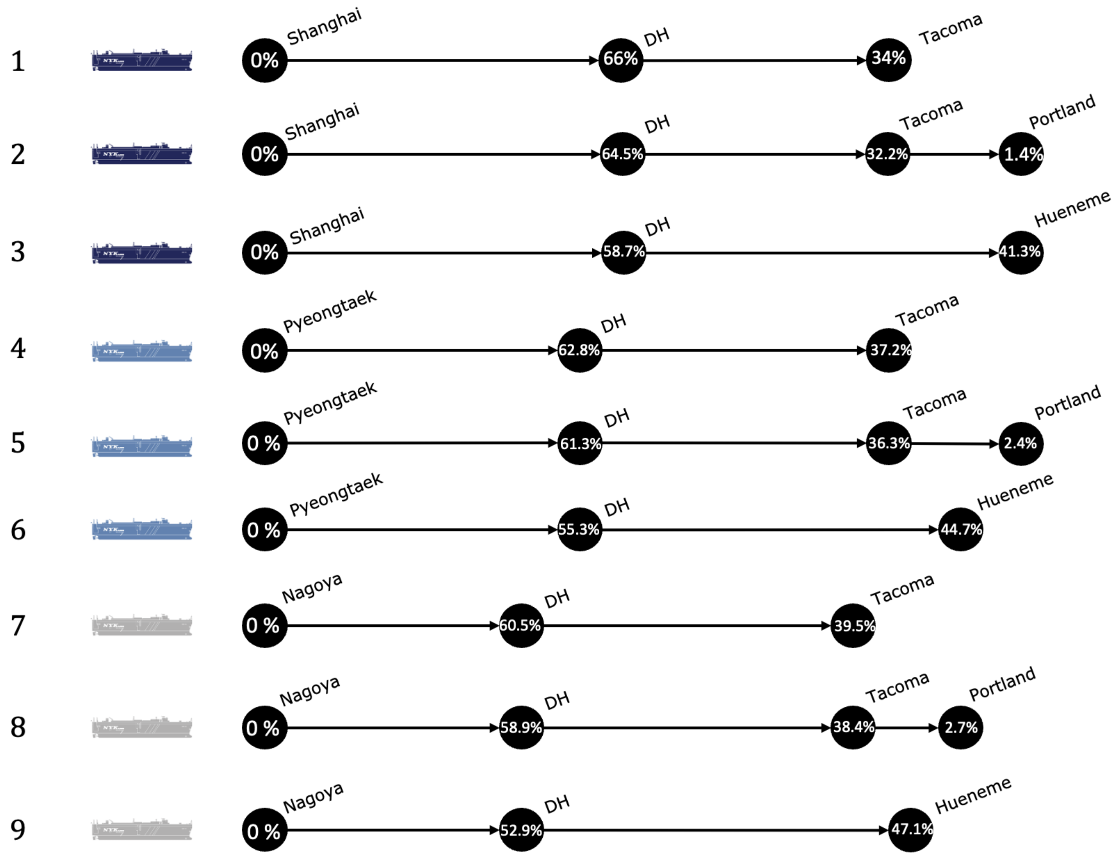


Figure 8.3: Percentage distribution of the amount of ammonia replenished on each route, baseline scenario.

Figure 8.2 pictures nine different sailing routes connecting each port in Northeast Asia with corresponding ports in the United States. Furthermore, the fuel hub in Dutch Harbour, with the geographical coordinate (54.13784, -166.51691), has been discovered to be the optimal location for energy replenishment between the two continents, with all nine vessels making replenishment stops in the location. Furthermore, Figure 8.3 reveals that Dutch Harbour accounts for more than half of the amount of ammonia replenished on a vessel's route. Additionally, the results reveal that additional energy replenishment on the corridor occurs in ports on the US west coast. This is reinforced by the fact that vessels 2, 5, and 8 must stop in Tacoma for a second energy replenishment stop before arriving in Portland. Table 8.2 also reveals three different energy storage capacity configurations of a PCC vessel, ranging from 4114 m^3 to 5211 m^3, depending on the route sailed.

8.3 Scenario 2: Variation in fuel price

The Northeast Asia-US green corridor may face a scenario in which the price of ammonia on each side of the corridor is significantly different. Price variations may influence the locations assigned for energy replenishment. Therefore, it is desirable to investigate how, or if, such a scenario will affect the selection of replenishment locations. The ammonia price in Asia doubled in the following scenario to 769.9 $\$/m^3$ from 384.8 $\$/m^3$ in the baseline scenario. Figure 8.4 shows the optimal sailing routes, while Table 8.3 gives the model results. Figure 8.5 displays the percentage distribution of the amount of ammonia replenished on each route generated by the model.

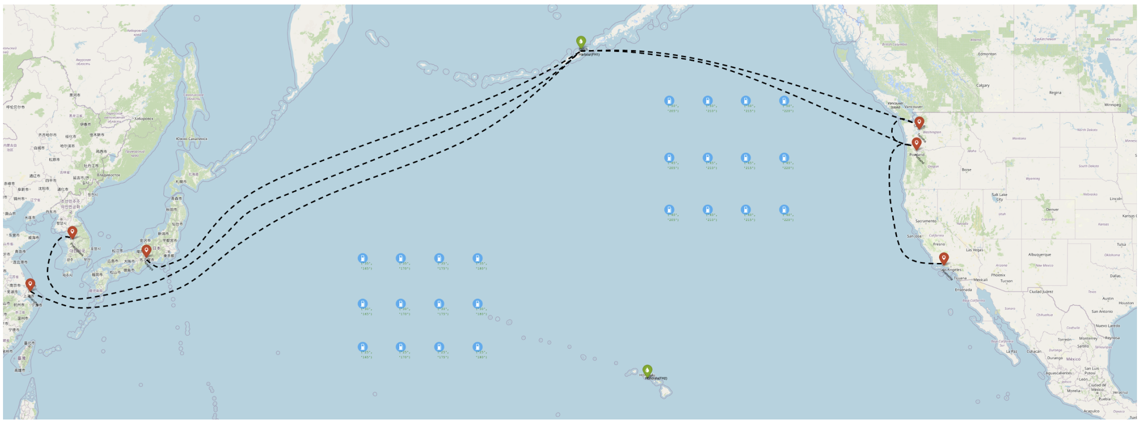


Figure 8.4: Optimal routes for high fuel price in Asia.

Table 8.3: Model results for high fuel price in Asia.

Vessel, v	**Optimal route**	**Ammonia replenished on route** $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - Dutch Harbour - Portland - Tacoma	5902	5211
2	Shanghai - Dutch Harbour - Tacoma - Portland	5902	5211
3	Shanghai - Dutch Harbour - Portland - Hueneme	6583	5211
4	Pyeongtaek - Dutch Harbour - Portland - Tacoma	5405	4525
5	Pyeongtaek - Dutch Harbour - Tacoma - Portland	5352	4525
6	Pyeongtaek - Dutch Harbour - Portland - Hueneme	6086	4525
7	Nagoya - Dutch Harbour - Portland - Tacoma	5108	4115
8	Nagoya - Dutch Harbour - Tacoma - Portland	5055	4115
9	Nagoya - Dutch Harbour - Portland - Hueneme	5789	4115

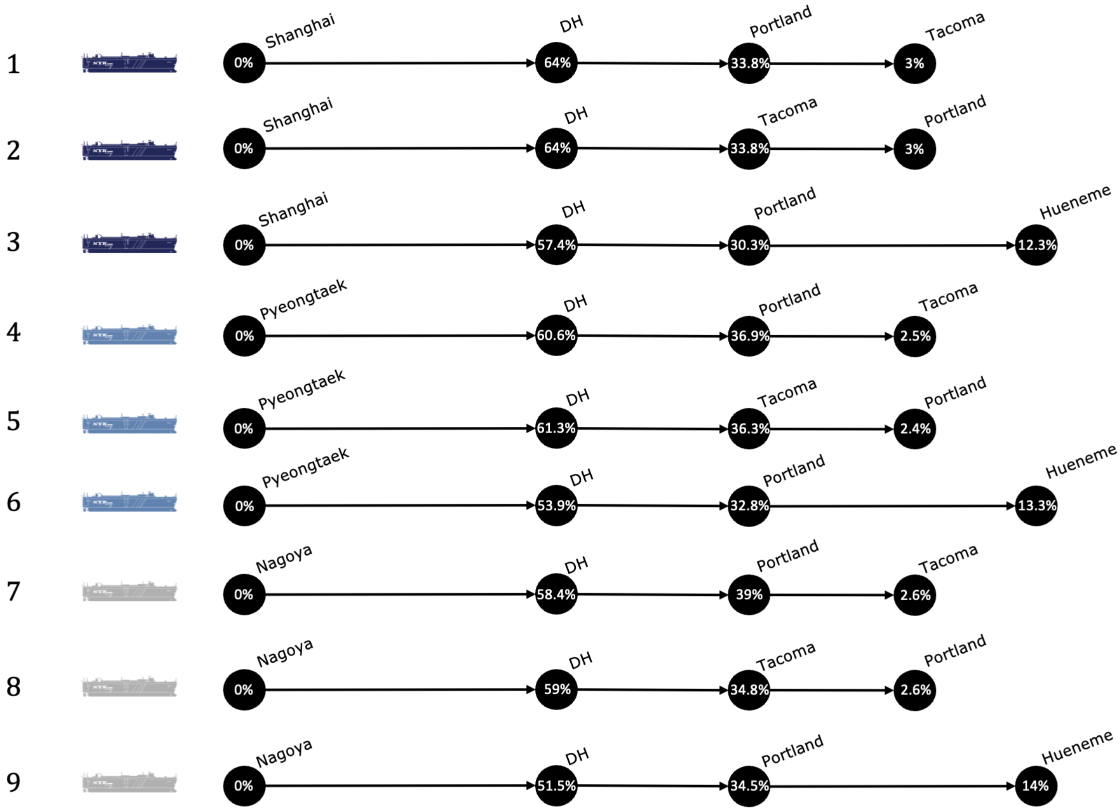


Figure 8.5: Percentage distribution of the amount of ammonia replenished on each route, high fuel price in Asia.

A rise in ammonia prices in Asia results in a network similar to the one generated by the baseline scenario. The observant reader, on the other hand, will notice minor differences. In the baseline scenario, all nine vessels sail directly from their respective ports of origin to Dutch Harbour to replenish their ammonia. This case also demonstrates the importance of the fuel hub. As seen in Figure 8.5, Dutch Harbour handles approximately 60% of the total amount of ammonia supplied on each route. Furthermore, both scenarios generate many of the same routes. However, the higher price of ammonia in Asia necessitates extra stops in both Portland and Tacoma for the vessels, with over 30% of the total amount of ammonia replenished on the routes happening in these ports. In terms of vessel configuration, Table 8.3 shows that the vessels' required energy storage capacity remains unchanged compared to the baseline scenario.

8.4 Scenario 3: Increase in energy consumption

The energy consumption of a 6500 ceu PCC vessel with an operational speed of 16 knots was estimated in Chapter 7.1.7. However, an increase in the operational speed is worth investigating because it may influence the selection of optimal locations and the required energy storage capacity of the vessels. Because energy consumption is closely related to vessel speed, a change in operational speed can be modeled by adjusting the energy consumption parameter, E_v^V, in the model. The following chapter investigates whether a change in vessel speed will influence the selection of energy replenishment locations, optimal routes for the fleet, and the required energy storage capacity. Figure 8.6 displays the optimal sailing routes generated from the model, while Table 8.4 gives the model results. Figure 8.7 presents the percentage distribution of ammonia replenished on each route.

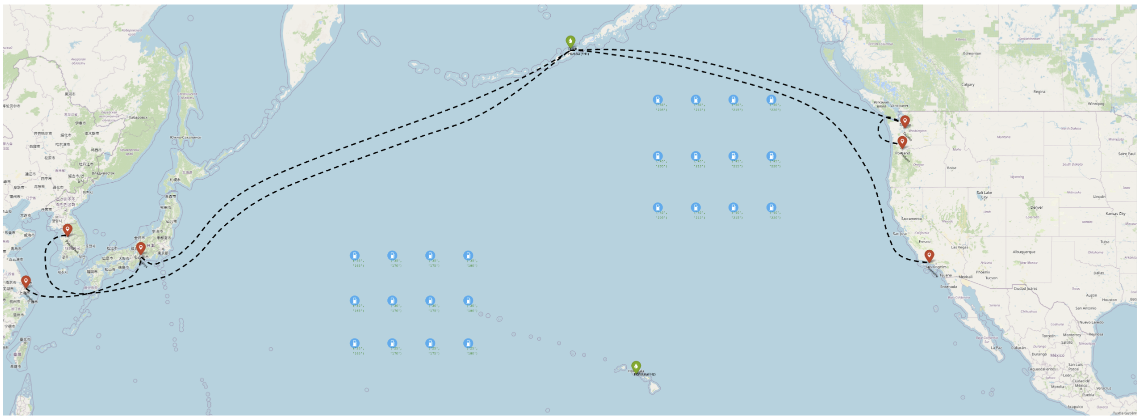


Figure 8.6: Optimal routes generated by increasing the energy consumption, E_v^V.

Table 8.4: Model results obtained by increasing the energy consumption, E_v^V.

Vessel, v	**Optimal route**	**Ammonia replenished on route** $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - Nagoya - Dutch Harbour - Tacoma	11668.7	8229.60
2	Shanghai - Nagoya - Dutch Harbour - Tacoma - Portland	11929.8	8229.60
3	Shanghai - Nagoya - Dutch Harbour - Hueneme	13080.1	8229.60
4	Pyeongtaek - Dutch Harbour - Tacoma	10443	9050.0
5	Pyeongtaek - Dutch Harbour - Tacoma - Portland	10703	9050.0
6	Pyeongtaek - Dutch Harbour - Hueneme	11854	9050.0
7	Nagoya - Dutch Harbour - Tacoma	9848.1	8229.6
8	Nagoya - Dutch Harbour - Tacoma - Portland	10109.3	8229.60
9	Nagoya - Dutch Harbour - Hueneme	11259.6	8229.60

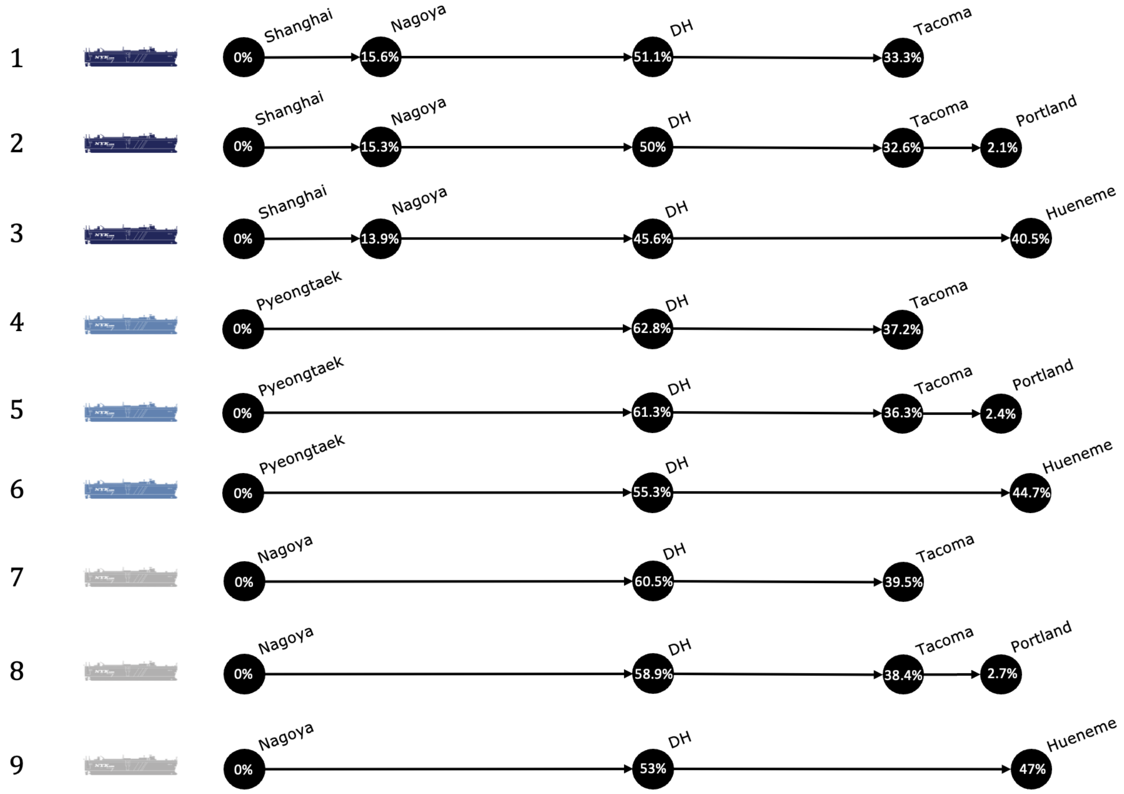


Figure 8.7: Percentage distribution of the amount of ammonia replenished on each route by increasing the energy consumption, E_v^V.

Figure 8.6 implies that increasing fuel consumption to 2.298 m^3/NM, which is twice the value compared to the baseline scenario, will produce several of the same optimal sailing routes. Simultaneously, the results reveal some deviations. As in the baseline scenario, the ships departing from Pyeongtaek and Nagoya appear to sail directly to Dutch Harbor for refueling. Furthermore, the ships departing from Shanghai will make a replenishment stop in Nagoya before sailing to Dutch Harbor for a second replenishment stop. As in previous scenarios, Dutch Harbor is a central replenishment location, as all nine ships refuel here. It is also worth noting that Tacoma is an important replenishment location, as vessels 2, 5, and 8 replenish in the port before sailing to their final destination in Portland. Additionally, table 8.4 reveals a required ammonia storage capacity of 8229.60 or 9050.0 cubic meters, depending on the route sailed. These values are significantly higher compared to those presented up until now.

8.4.1 Scenario 4: High energy consumption, low cost of fuel supply

The analysis from Chapter 8.4 continues by examining how the model responds to a combination of even higher sailing speeds and reduced fuel supply costs from the fuel hub to the offshore energy replenishment locations, C^{FHS}. As before, we simulate increased speed by increasing the energy consumption variable, E_v^V. The variable increases to 5.745 m^3/NM, five times the baseline scenario's energy consumption. Additionally, the cost of supplying fuel from the fuel hub, C^{FHS}, is set to 55 $\$/NM$, indicating a 50 percent reduction compared to the analysis from 8.4. Figure 8.8 displays the optimal sailing routes generated from the model. The black dotted line indicates the optimal routes generated by the model, while the red dotted lines represent the sailed route by the bunkering vessels. Furthermore, Table 8.5 gives the model results, while Figure 8.9 showcases an illustrative overview of the percentage distribution of the amount of ammonia replenished on each route.

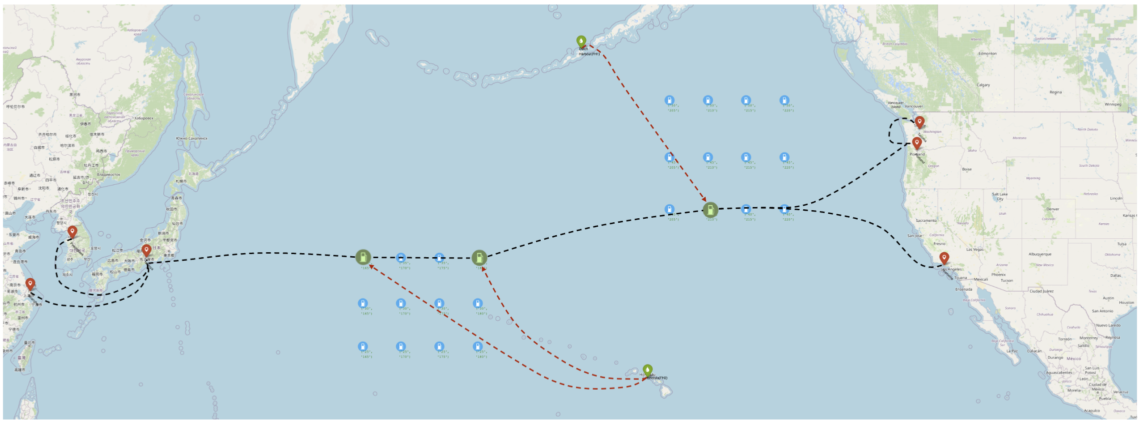


Figure 8.8: Optimal routes for high energy consumption and low cost of supplying fuel.

Table 8.5: Model results for high energy consumption and low cost of supplying fuel.

Vessel, v	Optimal route	Ammonia replenished on route $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland - Tacoma	32850.6	11519.0
2	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland	32197.6	11519.0
3	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Hueneme	33740.5	11961.0
4	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland - Tacoma	31082.6	11519.0
5	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland	30429.7	11519.0
6	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Hueneme	31972.5	11961.0
7	Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland - Tacoma	28299.3	11519.0
8	Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Portland	27646.4	11519.0
9	Nagoya - RL13(35,-195) - RL16(35,-180), RL10(40,-150) - Hueneme	29189.3	11961.0

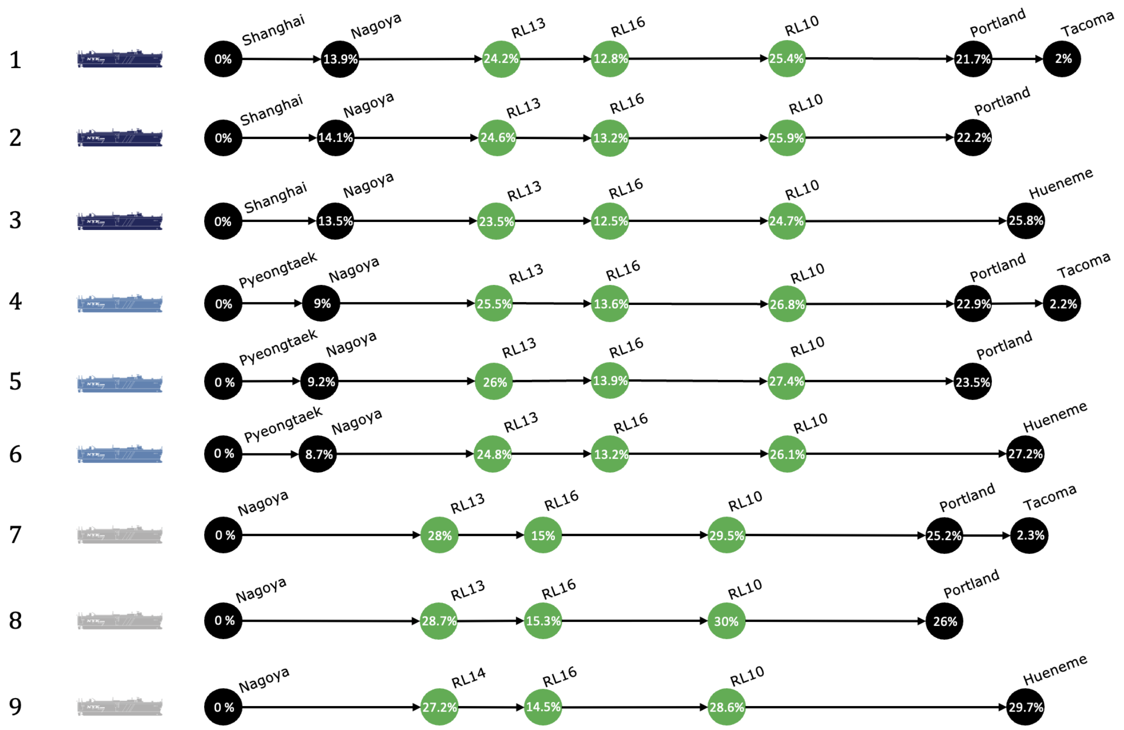


Figure 8.9: Percentage distribution of the amount of ammonia replenished on each route for high energy consumption and low cost of supplying fuel.

Because of the high energy consumption and the significant reduction in the cost of supplying fuel from the fuel hub, three offshore replenishment locations become part of the optimal solution. Figure 8.9 reveals that the fuel hub in Hawaii serves RL13 and RL16, with the geographical coordinates (35,-195) and (35,-180), respectively, while the fuel hub in Dutch Harbour serves RL10 with the geographical coordinate (40,-150). Furthermore, the ports of Nagoya and Portland emerge as vital in this scenario, as two-thirds of the fleet visit these ports for ammonia replenishment. At the same time, figure 8.9 implies that ammonia replenishment is more evenly distributed between designated locations and ports. Table 8.5 also reveals that the required storage capacity for the vessels has significantly increased compared to the scenario presented in 8.4 with required energy storage capacity as high as 11519.0 m^3.

8.5 Scenario 5: Increasing the lost opportunity cost

This chapter investigates how the lost opportunity cost, C_v^{LOC}, influences the model by increasing the parameter value. An increase in the lost opportunity cost simulates a scenario where the PCC vessel will need to pay a high price for the amount of ammonia stored in the vessel, which may be a reality if the PCC vessel seeks to make the transpacific voyage to the US without performing underway energy replenishment. This scenario estimates a lost opportunity cost of 306.6 \$, twice the parameter's value in the baseline scenario. Figure 8.10 presents the optimal routes generated, and the model results are listed in Table 8.6. Figure 8.11 presents a percentage distribution of the amount of ammonia replenished on each route.

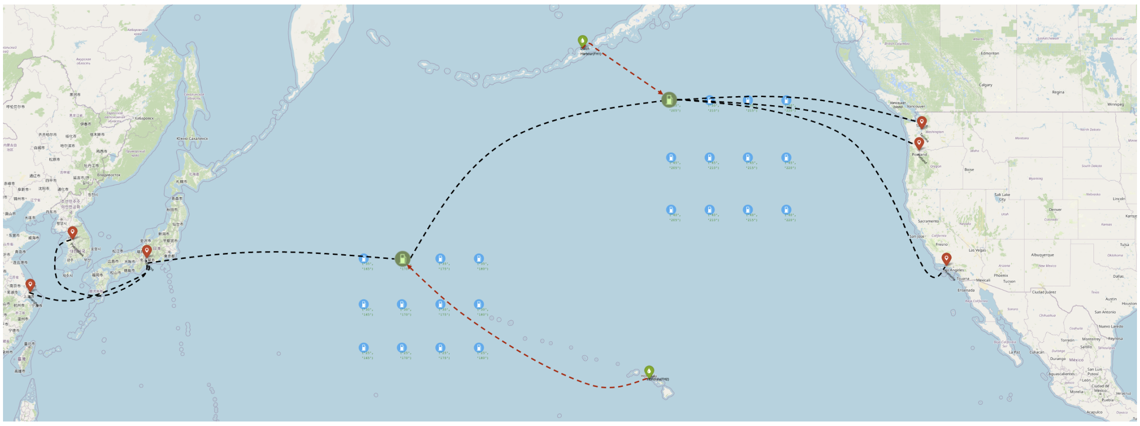


Figure 8.10: Optimal routes for increased lost opportunity cost ($2 \cdot C_v^{LOC}$).

Table 8.6: Model results for increased lost opportunity cost ($2 \cdot C_v^{LOC}$).

Vessel, v	**Optimal route**	**Ammonia replenished on route** [m^3]	k_v^{ES} [m^3]
1	Shanghai - Nagoya - RL14 (35,-190) - RL1 (50,-155) - Tacoma	6290.7	2804.6
2	Shanghai - Nagoya - RL14 (35,-190) - RL1 (50,-155) - Portland	6321.0	2804.6
3	Shanghai - Nagoya - RL14 (35,-190) - RL1 (50,-155) - Hueneme	6913.7	2903.6
4	Pyeongtaek - Nagoya - RL14 (35,-190) - RL1 (50,-155) - Tacoma	5937.2	2804.6
5	Pyeongtaek - Nagoya - RL14(35,-190) - RL1(50,-155) - Portland	5967.4	2804.6
6	Pyeongtaek - Nagoya - RL14(35,-190) - RL1(50,-155) - Hueneme	6560.2	2903.6
7	Nagoya - RL14(35,-190) - RL1(50,-155) - Tacoma	5380.5	2804.6
8	Nagoya - RL14(35,360-190) - RL1(50,360-155) - Portland	5410.7	2804.6
9	Nagoya - RL14(35,360-190) - RL1(50,360-155) - Hueneme	6003.5	2903.6

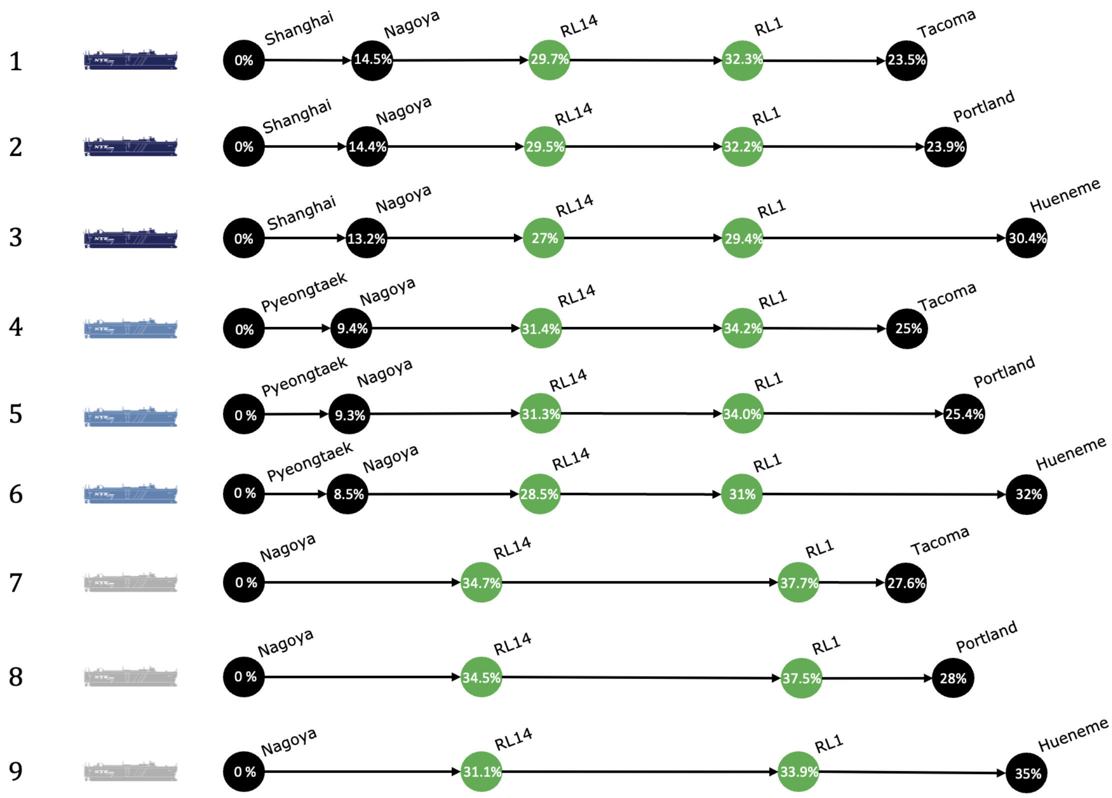


Figure 8.11: Percentage distribution of the amount of ammonia replenished on each route for increased lost opportunity cost $(3 \cdot C_v^{LOC})$.

By doubling the lost opportunity cost, a significant change in the optimal sailing route selection occurs compared to previously investigated scenarios. Figure 8.10 shows that two offshore replenishment locations are established in the Pacific Ocean, marked with a green symbol. The first offshore location, RL14, is located in (35,-190) and will be serviced by a dedicated bunkering vessel from the fuel hub in Hawaii. Similarly, Dutch Harbour serves offshore location number two, RL1, at the geographical coordinate (50,-155). The red dotted lines indicate the sailed route for the bunkering vessels. It is also worth noting that the port of Nagoya serves as a strategic refueling site in this scenario, as ships departing from Shanghai and Pyeongtaek make port calls in Nagoya to refuel before continuing into the Pacific. In other words, combined with the two offshore locations, Nagoya is critical for the PCCs crossing the Pacific, accounting for roughly 70% of the total fuel replenishment on the routes, as illustrated in Figure 8.9. It is also worth noting that neither of the nine ships must call at other ports in the United States before concluding their respective routes in the port of destination. Moreover, Table 8.6 show a required energy storage capacity of 2804.6 m^3 with a lost opportunity cost of 306.6 \$. This is a significant reduction compared to the baseline scenario and an even greater reduction compared to the high-energy consumption scenarios.

8.5.1 Scenario 6: Further increase in lost opportunity cost

The analysis from 8.5 continues by investigating how the model responds to a further increase in the lost opportunity cost. In this case, C_v^{LOC} holds a value of 459.9 \$, indicating three times the value of the lost opportunity cost in the baseline scenario. Figure 8.12 illustrates the optimal routes generated for the new environment. Moreover, table 8.7 provides the model results, and a percentage distribution of the amount of ammonia replenished on each route is found in Figure 8.13.

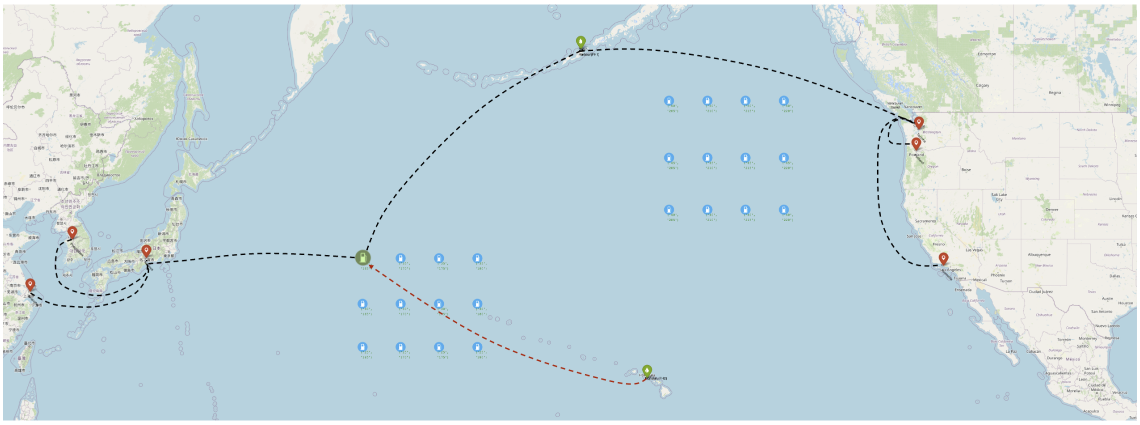


Figure 8.12: Optimal routes for further increase in the lost opportunity cost ($3 \cdot C_v^{LOC}$).

Table 8.7: Results for further increase in the lost opportunity cost ($3 \cdot C_v^{LOC}$).

Vessel, v	**Optimal route**	**Ammonia replenished on route** $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma	6340.9	2680
2	Shanghai - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Portland	6471.5	2680
3	Shanghai - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Hueneme	7274.6	2680
4	Pyeongtaek - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma	5987.3	2680
5	Pyeongtaek - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Portland	6117.9	2680
6	Pyeongtaek - Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Hueneme	6921	2680
7	Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma	5430.6	2680
8	Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Portland	5561.2	2680
9	Nagoya - RL13(35,-195) - Dutch Harbour - Tacoma - Hueneme	6364.4	2680

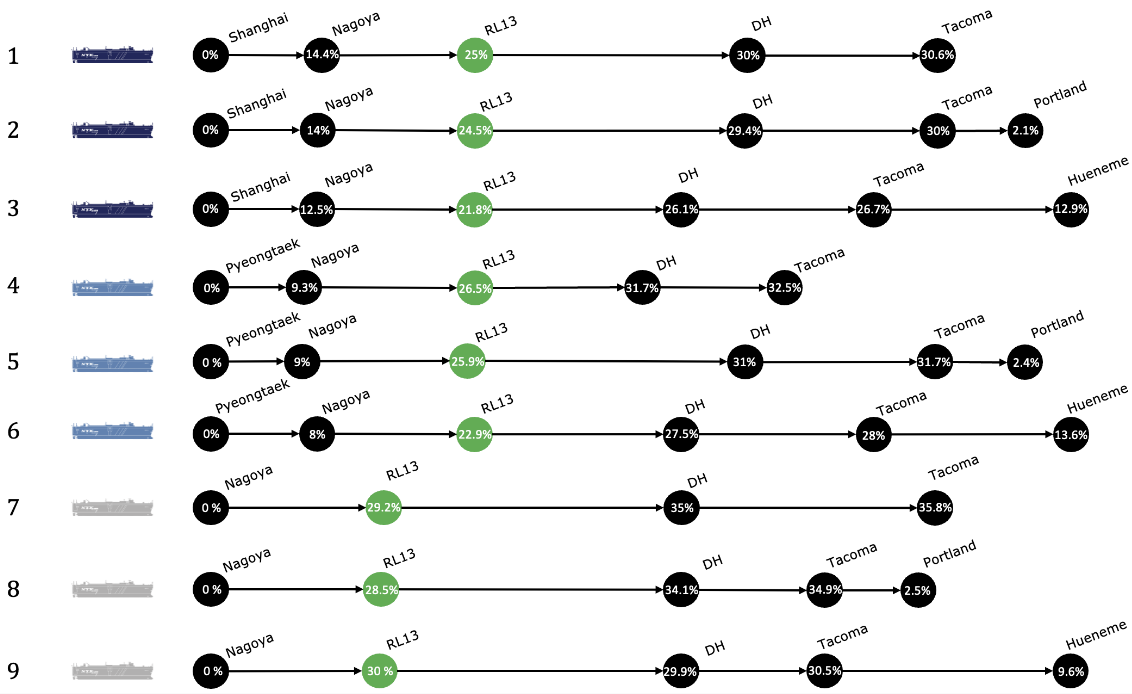


Figure 8.13: Percentage distribution of the amount of ammonia replenished on each route for further increase in the lost opportunity cost ($3 \cdot C_v^{LOC}$).

A further increase in lost opportunity cost generates a scenario different from the previous scenario presented in Chapter 8.5. At the same, similarities also occur in the following scenario. Figure 8.12 reveals only one offshore replenishment location as a part of the optimal solution. RL13 is established with the geographical coordinate (35,-195), serviced by the fuel hub in Hawaii. Furthermore, it emerges that the vessels sail on to Dutch Harbor for a new supply of ammonia before the journey continues to the ports on the west coast of the US. In addition to RL13 and Dutch Harbour, our results also emphasize Nagoya and Tacoma as optimal and strategic locations for refueling ammonia. Six out of nine vessels visit Nagoya for energy replenishment, while all vessels visit Tacoma, as illustrated in Figure 8.13. According to Table 8.7, a further increase in the lost opportunity cost also results in a further reduction in the required ammonia storage capacity for the vessels. However, such a decrease is relatively small compared to the reductions between the baseline scenario and a doubling of the lost opportunity cost.

8.6 Scenario 7: Self-serviced offshore locations

The following scenario investigates how the model handles independent offshore replenishment locations. In such a scenario, the optimal offshore locations selected by the model produce and distribute ammonia and are not dependent on the Dutch Harbour and Hawaii as fuel hubs. It is possible to model such an environment by letting the fuel supply cost from the fuel hubs to the offshore locations, C^{FHS}, be equal to zero. Figure 8.14 pictures the optimal routes selected by the model and the corresponding replenishment locations, while Table 8.8 gives an overview of the results obtained from the model. As for previous scenarios, Figure 8.15 showcases a percentage distribution of ammonia replenished on each route.

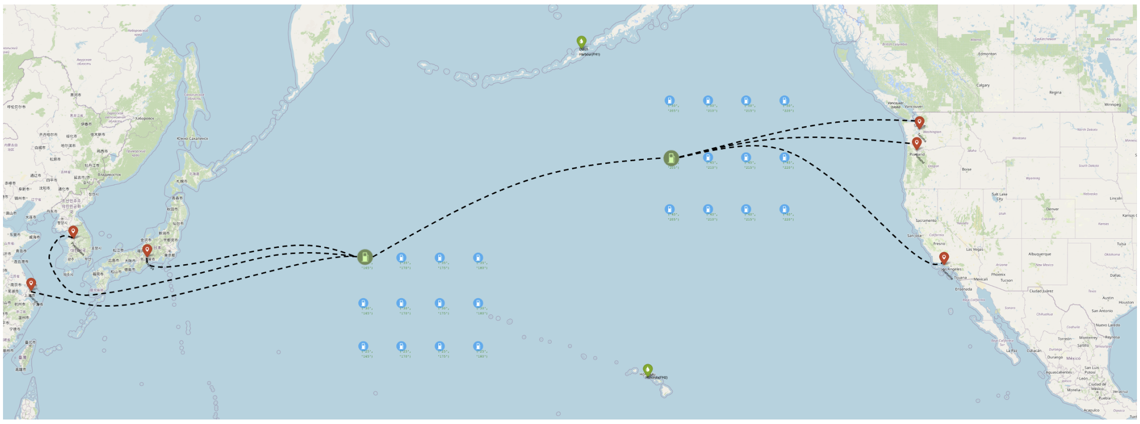


Figure 8.14: Optimal routes for independent offshore locations ($C^{FHS} = 0$).

Table 8.8: Model results for independent offshore locations ($C^{FHS} = 0$).

Vessel, v	**Optimal route**	**Ammonia replenished on route** $[m^3]$	k_v^{ES} $[m^3]$
1	Shanghai - RL13(35,-195) - RL5(45,-155) - Tacoma	6248.9	3445.8
2	Shanghai - RL13(35,-195) - RL5(45,-155) - Portland	6249.5	3445.8
3	Shanghai - RL13(35,-195) - RL5(45,-155) - Hueneme	6720.0	3445.8
4	Pyeongtaek - RL13(35,-195) - RL5(45,-155) - Tacoma	5857.0	3033.6
5	Pyeongtaek - RL13(35,-195) - RL5(45,-155) - Portland	5857.7	3033.6
6	Pyeongtaek - RL13(35,-195) - RL5(45,-155) - Hueneme	6328.3	3033.6
7	Nagoya - RL13(35,-195) - RL5(45,-155) - Tacoma	5340.0	3033.6
8	Nagoya - RL13(35,-195) - RL5(45,-155) - Portland	5340.6	3033.6
9	Nagoya - RL13(35,-195) - RL5(45,-155) - Hueneme	5811.2	3033.6

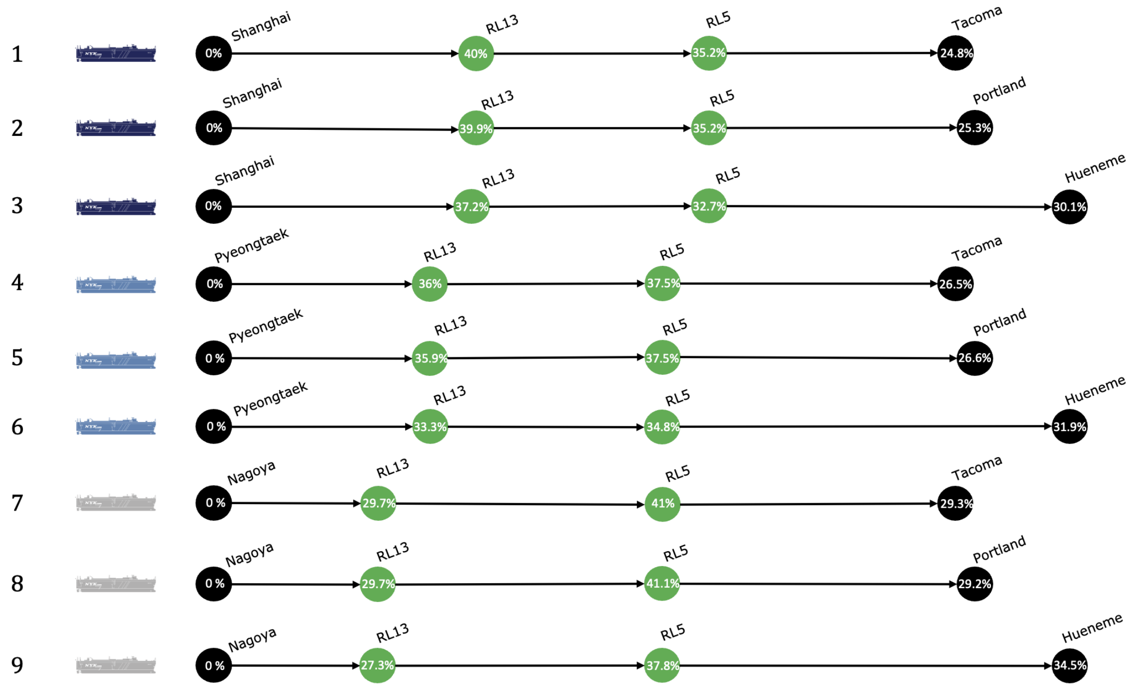


Figure 8.15: Percentage distribution of the amount of ammonia replenished on each route for independent offshore locations ($C^{FHS} = 0$).

The model discovers two of the 24 offshore locations, marked green, as part of the optimal solution by allowing the offshore energy replenishment locations to be self-serviced. As for some of the previous scenarios, all nine vessels make a visit to RL13 for replenishment of ammonia. Additionally, RL5, with the geographical coordinates (45,-155), becomes a part of the optimal solution and serves as the second offshore replenishment location on the routes. It should also be noted that all vessels are sailing directly to the optimal replenishment locations without any additional replenishment stops in any of the other ports on the corridor, which has been the case in several previous scenarios. Moreover, Table 8.8 shows that the required storage capacity for the vessels is either $3033.6m^3$ or $3445.8m^3$, depending on the route sailed by the vessel.

8.6.1 Scenario 8: Self-serviced offshore locations continued

The scenario from 8.6 is extended in this chapter to identify how the model responds to a further change in the input parameters given a C^{FHS} value equal to zero. As the lost opportunity cost has significantly influenced the model in previous scenarios, it is once more selected as the variable to be adjusted. Figure 8.16 presents the optimal routes, while Table 8.9 highlights the model results. Additionally, Figure 8.17 displays the percentage distribution of ammonia replenished on each route.

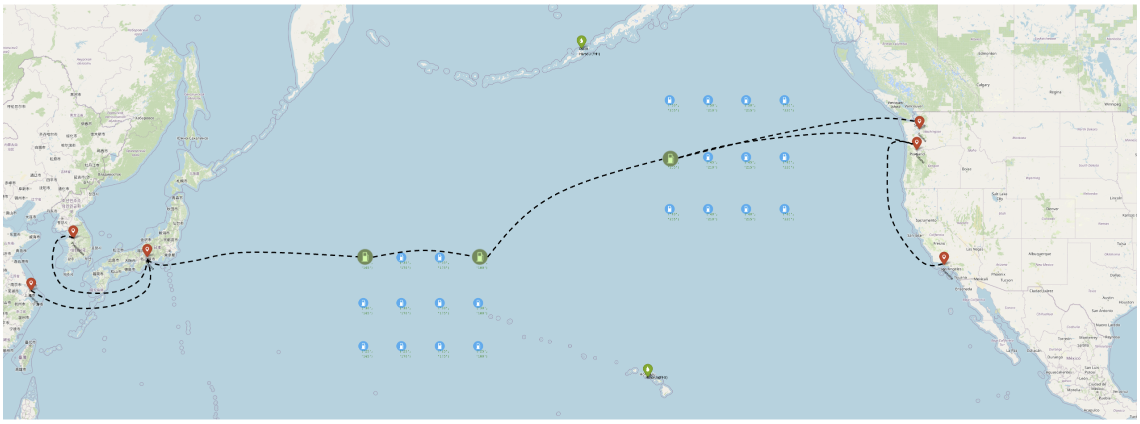


Figure 8.16: Optimal routes for independent offshore locations and increased lost opportunity cost ($C^{FHS} = 0,\ 2 \cdot C_v^{LOC}$).

Table 8.9: Model results for independent offshore locations and increased lost opportunity cost ($C^{FHS} = 0,\ 2 \cdot C_v^{LOC}$).

Vessel, v	**Optimal route**	**Ammonia replenished on route $[m^3]$**	k_v^{ES} $[m^3]$
1	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Tacoma	6380.8	2191.6
2	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland	6381.4	2191.6
3	Shanghai - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland - Hueneme	7192.9	2191.6
4	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Tacoma	6027.2	2191.6
5	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland	6027.8	2191.6
6	Pyeongtaek - Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland - Hueneme	6839.3	2191.6
7	Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Tacoma	5470.5	2191.6
8	Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland	5471.0	2191.6
9	Nagoya - RL13(35,-195) - RL16(35,-180) - RL5(45,-155) - Portland - Hueneme	6282.6	2191.6

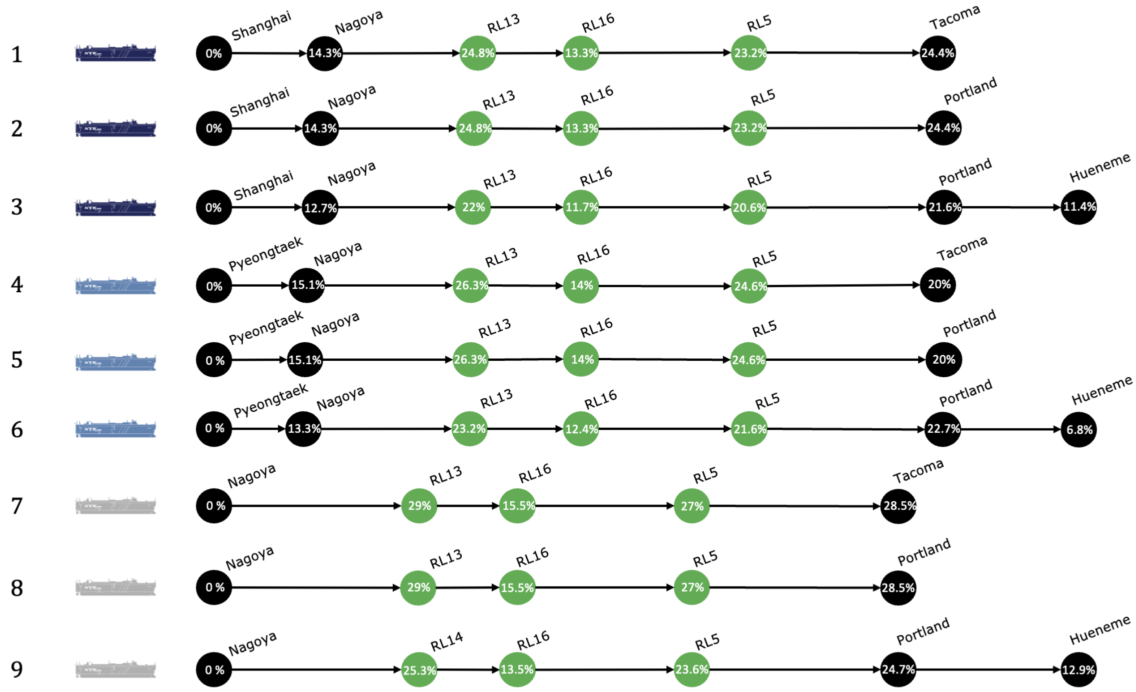


Figure 8.17: Percentage distribution of the amount of ammonia replenished on each route for independent offshore locations and increased lost opportunity cost, ($C^{FHS} = 0, 2 \cdot C_v^{LOC}$).

Three offshore replenishment locations are established by letting C^{FHS} equal zero and adjusting C_v^{LOC} to 306.6 \$, twice the parameter's value in the baseline scenario. As in the scenario from Chapter 8.6, RL13 and RL16 are a part of the optimal solution. Additionally, RL5 taking the geographical coordinates (45,-155) becomes a part of the optimal solution. In this scenario, the Port of Nagoya is also a strategic location for ammonia replenishment, as vessels 1-6 visit the port for replenishment before continuing into the Pacific. Likewise, the Port of Portland is a strategic location as vessels 3, 6, and 8 make replenishment stops there. Furthermore, a third offshore replenishment location adds to the solution, and an increase in C_v^{LOC} results in a reduction in the required energy storage capacity for the vessel, as seen in Table 8.9.

Chapter 9

Discussion

In this chapter, the results from the case study and related topics are discussed. The chapter is divided into two parts. First, a discussion of the results obtained from the case study, covering all scenarios presented in Chapter 8. Then, a more general discussion on other relevant aspects related to the case study, model development, and topics presented in this thesis.

9.1 Case study results

The results presented in Chapter 8 reveal that energy replenishment at one or more locations along the trade lane can be a suitable solution for ammonia-fueled PCC vessels. All ships carrying out refueling en route in all scenarios investigated support such a statement. However, there is also a significant variation in the optimal locations chosen by the model, demonstrating that some input parameters have more influence on the model than others. Both in terms of required energy storage capacity and optimal routes generated.

9.1.1 The baseline scenario

Chapter 8.2 establishes the baseline scenario by specifying estimated cost and volume parameter values in the mathematical optimization model. As previously mentioned, these values rely on mathematical calculations and other research. Simultaneously, it is critical to emphasize that the parameter values arrived at in the baseline scenario must be seen in the context of limited access to data on ammonia as a ship fuel. It mainly applies to data on fuel consumption, costs, and occupied volume of machinery and propulsion components. Therefore, further research into the input parameters may lead to deviations from the results obtained in the baseline scenario. Both in terms of parameter values and optimal routes generated. Nevertheless, the parameter values presented have been carefully evaluated to provide the most realistic case possible. Furthermore, one observes that the baseline scenario only generates one single replenishment location underway on the routes, which is also true when specific parameters are further adjusted in later scenarios. The model also selects the land-based fuel hub in Dutch Harbor as the optimal location between the continents, ignoring the 24 alternative offshore locations. Such a result may indicate that the cost of supplying ammonia to the offshore locations is too high to include them in the optimal solution. Another contentious outcome emerges from the baseline scenario. The Port of Tacoma serves as a second replenishment stop for routes ending in Portland. It is debatable whether this refueling stop is even necessary on these routes, given that the distance from Dutch Harbor to Portland is only about 45 nautical miles longer than the distance to Tacoma. Going directly from Dutch Harbour to Portland may be a better solution than the one generated from the model. However, such a statement will require further research into the model development. The variation in required energy storage capacity generated by the model is essential in all scenarios investigated, and the baseline scenario is no exception. The observant reader may raise an eyebrow because storage capacity is typically a fixed parameter on a vessel. Its explanation, however, lies in the mathematical model, which allows the required energy storage capacity to be variable and indicates different vessel configurations for different routes sailed. The baseline scenario indicates that between 4100 and 5300 cubic meters are required. These figures are significantly higher than the fuel tank capacity of conventionally fueled PCC ships, which have a tank capacity of around 2000 to 3000 cubic meters.

9.1.2 Variation in fuel price

By doubling the ammonia price in Asia, one discovers that adjusting the price only causes minor changes to the results. Several of the arcs traveled in the baseline scenario are present in the new one, and the fuel hub in Dutch Harbour is visited by all vessels. Assessing what happens when the vessels depart Dutch Harbour reveals the most significant deviation from the baseline scenario. Due to high Asian fuel prices, the model includes additional refueling stops in US ports. The fact that it will be more appropriate to go directly to locations on the American shelf to replenish ammonia due to the high prices in Asia may explain such an outcome. However, further research into how the cost variable influences the model is necessary to say anything more about how it influences the model. Additionally, it is noted that the required energy storage capacity of the vessels holds the same values as in the baseline scenarios. Such findings indicate that the fuel cost does not influence the energy storage capacity in the scenario.

9.1.3 Increase in energy consumption

The case study analysis continues by considering how an increased sailing speed affects the model. A sensible way of doing so is to increase the energy consumption variable in the model. However, it is required to specify that the energy consumption is only doubled from the baseline scenario and does not necessarily correspond to a specific sailing speed suitable for a PCC vessel, which is the case in the baseline scenario. A more suitable approach could have been calculating the energy consumption for different sailing speeds and then using these values as input to the model. Our approach should only be considered a simplification demonstrating that increased sailing speed will increase fuel consumption. That said, doubling the energy consumption makes a relatively small difference in the optimal routes generated. The only significant difference compared to the two previous scenarios is the fact that the model introduces the port of Nagoya as an additional location for refueling. However, it is discovered that this only holds for the vessels starting their voyages from Shanghai. Not surprisingly, total energy storage capacity has increased significantly compared to the two previous scenarios. A doubling of energy consumption necessitates an increase in required storage capacity of 3019.2, 4525, and 4110.8 cubic meters, depending on the route sailed. These are relatively significant increases but can be defended by the combination of high energy consumption and long sailing distances between ports and replenishment locations visited in the scenario.

9.1.4 Increase in energy consumption, reduction in the cost of fuel hub supply

Testing the model for modifications in fuel price and energy consumption remains to benefit from finding an offshore location as part of the optimal solution. So far, Dutch Harbour is the preferred replenishment location between the continents in the corridor, and the feasibility of offshore energy replenishment remains to be discovered. It is, therefore, only natural to continue the analysis and focus on how or if these locations can become a part of an optimal solution. Compared to the scenarios discussed, an entirely new network of sailing routes is discovered by significantly increasing energy consumption to five times the baseline scenario's value and decreasing fuel supply costs from the fuel hub. Concerning model testing, this case adjusts two parameters simultaneously. It marks a new strategy for testing the model. Unlike previous scenarios where only one parameter was adjusted, the results show that such a strategy affects the model. Furthermore, adjusting the energy consumption and cost of the fuel hub supply will result in the vessels carrying out two to three more replenishment stops compared to previous scenarios. Vessels replenish their ammonia at offshore locations and ports, and the energy replenished is distributed relatively evenly across the visited locations. The entrance of the offshore replenishment locations can be seen in context with the decrease in the cost of fuel hub and the high value of energy consumption, and is not a far-fetched outcome. However, whether the new values selected represent, a real-life scenario can be discussed. As debated earlier, it is difficult to thoroughly indicate what the increase in energy consumption corresponds to in terms of operational speed for the vessels. A value of five times the energy consumption in the baseline scenario might reflect an excessive operational speed for the PCC vessel. Therefore, this model scenario can also benefit from pre-calculating energy consumption for different operational speeds. Moreover, this scenario demonstrates that both fuel hubs are important as Dutch Harbor and Hawaii serve the optimal offshore locations. Such a result demonstrates that both fuel hubs can play a vital role in the corridor, given the right circumstances. Furthermore, the required energy storage capacity has increased significantly compared to previous scenarios. With a significant increase in energy consumption, the required storage capacity rises to 11,500 cubic meters, a relatively significant increase compared to previous tests. The high energy consumption may justify such a value. However, it also demonstrates that this scenario requires more research on the effect of increased fuel consumption due to the significant disparity.

9.1.5 Lost opportunity cost

An increase in the lost opportunity cost per cubic of stored ammonia results in several interesting outcomes. The validity of offshore energy replenishment is again demonstrated as the model can identify offshore replenishment locations as part of the optimal solution. With a lost opportunity cost twice the value of the baseline scenario, the number of offshore replenishment locations is reduced to two locations. Simultaneously, it emerges that an increase in lost opportunity costs leads to replacing one of the offshore locations with the fuel hub in Dutch Harbor. Such a result indicates that, under the right conditions, a combination of offshore and onshore replenishment between the continents could be an optimal solution. Until now, such an outcome has not been demonstrated, and it adds another solution to the results and further strengthens the concept of underway replenishment on the corridor. By increasing the opportunity cost, another significant outcome emerges. Compared to previous scenarios, the required energy storage capacity is significantly lower. The only exception is a scenario with high energy consumption and low fuel costs from the fuel hub. However, whether this is a reasonable scenario for the corridor is debatable. Nonetheless, the results obtained for an increase in the lost opportunity cost show that refueling at strategic locations between the two continents results in ships having more than half the energy storage capacity of the baseline scenario. The model compensates for the lost opportunity cost by adding more energy replenishment locations to the optimal solution, making it more economically advantageous to perform energy replenishment.

Such a result is one of the most important findings from the case study. At the same time, it is critical to emphasize that the lost opportunity cost is very influential in the amount of energy replenishment operations performed en route. Such characteristics will require good strategies and methods for how such a cost can best be calculated and connected to higher occupied volume due to ammonia utilized as fuel. In this thesis, rough estimates are made by comparing the volume of a car to the volume of ammonia. Such a strategy does not necessarily accurately estimate a reasonable lost opportunity cost. There may also be other factors that can influence such a cost parameter. It includes factors such as the number of voyages, the ship's lifetime, and the cargo's price. For these reasons, further research is also necessary in this area.

9.1.6 Independent offshore locations

Investigating what happens by leaving the offshore locations independent is a natural final step in the model test process, primarily because such a scenario is highly feasible in a future green shipping corridor. It may also be a more appealing long-term alternative to land-based fuel hubs with associated bunker vessels. This study's independent offshore locations scenarios refer to offshore energy replenishment locations independent of the fuel hubs established in Dutch Harbour and Hawaii. Such a case implies that the replenishment locations must capitalize from other offshore fuel production concepts such as floating wind, FPSO, and replenishment, research, and rescue vessel concepts such as Ulstein Thor. At the same time, it is crucial to consider that the Pacific Ocean has an average depth of around 4300 meters, which makes it challenging to use technologies that require mooring systems as this would be too expensive and technically demanding to implement on such depts. Therefore, energy replenishment vessel concepts such as *Ulstein Thor* and *MS Green Ammonia*, earlier introduced in the thesis, might be the only realistic solution in this geographical area. Additionally, the floating ammonia production unit concept by SwitchH2 and BW Offshore should also be highlighted as a feasible and suitable option for the transpacific corridor.

Furthermore, the model simulates independent offshore locations by letting the cost of fuel hub supply be equal to 0. By doing so, it will be natural to expect that at least one or more of the 24 alternative offshore locations will be part of the optimal solution. The two scenarios presented in Chapter 8.6 largely support such a claim. With a cost of fuel hub supply equal to zero, two of the 24 offshore locations become part of the optimal solution, while a doubling in the lost opportunity cost results in an additional location added to the optimal solution. The initial claim is thereby confirmed, further strengthening the versatility of the mathematical optimization model presented in this thesis. It also emerges that the required energy storage capacity takes somewhat higher values than a doubling of the lost opportunity cost. However, it remains lower than the values obtained in the baseline scenario. Moreover, the negative correlation between required energy storage capacity and lost opportunity cost is still valid through the scenarios presented in Chapter 8.6. Additionally, our findings confirm that performing underway replenishment can compensate for the high required energy storage capacity under specific circumstances.

9.2 Optimization model

The optimization model presented in the case study demonstrates success in many cases. It is a generic model demonstrating success in several different cases and scenarios. However, it is relatively limited, and it is natural to develop the model further to simulate realistic scenarios better. The following chapter discusses the optimization model by addressing limitations, input parameters, and future model extensions.

9.2.1 Limitations and possible model extensions

The optimization model presented in this thesis is limited, and several simplifications have been made. One of these simplifications is the use of discrete offshore energy replenishment locations. The model includes 24 predetermined offshore locations separated into two grids and positioned near the fuel hubs. Such a strategy certainly does not represent a realistic scenario, as refueling, in reality, can occur anywhere between the two continents. Simulating a more realistic scenario will be possible by allowing the offshore locations to be continuous. Such a measure implies that the PCC vessels can move freely to any geographical location in the corridor. Another option is to keep the offshore energy replenishment locations discrete and create a more extensive grid covering the whole corridor. It has been demonstrated earlier in this thesis that the model can handle more extensive grids of offshore energy replenishment locations. Nevertheless, this is admittedly using significantly smaller distances and values that do not represent a realistic case study. It will therefore be natural that the model must be tested for a more complex node network before such a claim can be denied or verified.

Time constraints and time periods are other limitations demonstrated by the model. This is true for the intended bunkering vessels and the PCC vessels. As previously described, it is only assumed that bunker vessels will meet the PCC vessels at the optimal locations when the PCC vessel arrives. However, a realistic scenario may include time windows where the PCC vessel gives a time interval when energy replenishment is required. Both hard and soft time windows could be part of a realistic scenario. Other aspects, such as the service time at each replenishment location, traveling time between each location, and the maximum duration of a route, have not been included in the model. Further model development should therefore emphasize suitable time constraints to model a more realistic logistical solution.

Furthermore, the model has only considered a single lost opportunity cost. In the case study model, this cost parameter connects to the occupied volume of ammonia in the ship hull. However, assuming that a PCC vessel will have more lost opportunity costs associated with performing underway replenishment is not unreasonable. A solution where the vessels refuel en route may increase the total time spent across the Pacific, which might cause fewer trans-Pacific voyages to be made annually. Over an extended period, such circumstances might lead to fewer cars distributed to the market, reducing the fleet's carrying capacity due to replenishment en route. Consequently, adding a lost opportunity cost due to underway energy replenishment to the model could be a reasonable extension.

With these considerations in mind, future model development should examine how refueling affects total fleet capacity and whether it can be modeled using a lost opportunity cost variable or time period constraints.

Another limitation to be aware of is that the model only considers ammonia as a fuel. Various alternative fuels and energy carriers will characterize green corridors and shipping in general, and ammonia will likely not emerge as the only fuel of choice. As a result, it is not unreasonable to propose other types of low-carbon fuels to the model. Such an extension can be implemented by, e.g., creating an additional set describing different alternative fuels and building new constraints based on such a set. However, only certain alternative energy carriers will be relevant to implement in the model. This is particularly true for those with a low volumetric density or those demonstrating limited range. The most appealing energy carriers to investigate in northeast Asia, US green corridor will likely be hydrogen, LNG, and methanol. Further model development could thus include these energy carriers as an option for the vessels.

9.2.2 Input parameters

There is some uncertainty related to the input parameters in the model, and it primarily applies to the values given to the cost and volume parameters. However, the number of vessels, ports, and fuel hubs selected in the study can also cause uncertainty. Uncertainty in cost and volume parameters occurs because it is challenging to estimate the actual costs and volumes, as several factors influence these parameters. The limited experience with ammonia as a marine fuel also significantly contributes to such uncertainty. At the same time, this thesis tries to adhere to reasonable values through careful research and estimation strategies. However, additional research into the cost and volume parameters could have resulted in a completely different baseline scenario and subsequent scenarios, as these are an extension of the baseline scenario.

The number of vessels selected can also lead to uncertainty. Nine vessels were selected to create three different routes from each port of origin. It is debatable whether this is realistic, and some of the routes generated may also not be realistic in a real scenario. Further model validation may emphasize the number of vessels selected for the model. It could be interesting to see whether, e.g., six or twelve vessels would make any difference in the routes generated. It could even be an option to generalize the fleet by only investigating one vessel and assigning different ports of origin and ports of destination to the vessel. Such a strategy could have generated the same routes as the ones presented in this thesis results. However, it will require adjustments in the model implementation process.

Additionally, the case study reveals that if the green corridor needs to establish strategic land-based fuel hubs, the alternative land areas between the continents will be relatively limited. It is, therefore, necessary to execute further research on whether the selected locations are suitable for the production and distribution of ammonia. Further research particularly applies to Dutch Harbour, an isolated geographical area with little port infrastructure compared to other places in the USA. At the same time, our case study shows that a fuel hub in Dutch Harbour can become exceedingly central in the corridor. Further research should therefore emphasize the required infrastructure in the area. A fuel hub in Hawaii could, however, be a better option. Undoubtedly, Hawaii has a more well-developed harbor area than Dutch Harbour. Additionally, several scenarios from the case study revealed offshore energy replenishment using bunkering vessels from Hawaii. Nevertheless, such a fuel hub will also require more research on producing and distributing ammonia and other alternative fuels on these islands.

9.3 Vessel segment

Selecting PCCs as the preferred fleet segment is a strategic choice. Mainly because the segment has good preconditions for being part of a green shipping corridor. A combination of small fleet size and few operators in the market can leverage and accelerate coordinated action between the stakeholders, which is crucial for the success of a green corridor. However, the optimization model presented in this thesis is not necessarily specialized for PCC vessels. As a result, it is reasonable to expect that it will be equally applicable to other ship segments. In order to decide whether it would be appropriate to continue the model development and the applicability to PCCs and other vessel segments, a thorough analysis of the actual amount of vessels making the transpacific journey will be beneficial, in addition to how often they complete the journey. Utilizing AIS data can significantly help here, and further corridor research should capitalize on such data, if available. In the long term, green corridors will see several vessel segments powered by alternative fuels. Therefore, logistical solutions demonstrating success in various vessel segments must be emphasized. Underway energy replenishment may be one such solution.

9.4 Ammonia as an energy carrier for shipping

The industry agrees that ammonia will be a suitable alternative for shipping and points to late 2025 or early 2026 as the dates when ammonia-powered ships are likely to hit the water. This is only about three years away from now. However, even then, it is expected to be much more work ahead before ammonia truly takes hold. Ammonia has its appeal in its chemical formula, NH_4. It has no carbon and takes up less space than hydrogen, whose low energy density is a significant challenge. Most ammonia today is made through processes that have high greenhouse gas emissions. It is undoubtedly a fact that the success of ammonia in the future will rely on making the fuel from hydrogen produced with renewable electricity in a zero-carbon way, i.e., green ammonia or with carbon capture, known as blue ammonia, which will become more cost-effective. In fact, while green hydrogen is considered the holy grail of shipping, it turns out that ammonia is the most efficient way of carrying hydrogen, and several initiatives have investigated the option of distributing hydrogen by transporting it through ammonia. Such ambitions underline the importance of ammonia beyond its use as fuel for ships. However, several factors are setting the timetable for ammonia-fueled shipping. One is regulation, and there are currently no global rules for using ammonia, and in fact, IMO regulations are currently discouraging it. However, an IMO committee is working to address that (TradeWinds 2023).

Another critical factor is the development of engines by major providers like MAN and Wärtsila. Key to that is to address the safety concerns as the fuel is toxic to human health. While carrying ammonia by ship happens every day, there are still challenges to overcome when using it in an engine. However, several stakeholders in the industry believe those challenges will be overcome, and some even argue that safety concerns have become too emotional. The speed of uptake of the technology, i.e., how fast the transition will go, is considered a critical factor. If the technological transition is more prolonged, engine providers will have more time to develop, but the task will be more prominent in the short term if the transition accelerates (TradeWinds 2023).

Even if several ships are on the water and can run on ammonia in the next few years, that is just another milestone in a longer journey. It could be as long as 2030 before international rules and regulations for ammonia fueling are in place, meaning projects until then will face a more complex approval process. Additionally, another challenge will arise as the seafarers must undergo the necessary training to work with ammonia on their vessels. Moreover, engine makers are currently utilizing a strategy to develop one or two engines suitable for specific vessel sizes. These engine configurations will be thoroughly tested and must be successful before engine makers invest in developing more engine sizes. Such a strategy implies that if vessel owners need an engine different from the size of the first wave of engine design, they might have to wait longer to build their ships (TradeWinds 2023).

Shipping will also need to access truly carbon-free ammonia all the way up to the production supply chain in order to succeed. Right now, most ammonia is essentially a fossil fuel, and more projects ramping up the supply of green and blue ammonia should come to life.

9.5 Energy replenishment as a measure for green shipping corridors

This thesis presents green shipping corridors and a logistical solution for refueling alternative fuels as a possible measure to accelerate green corridors. The purpose of green corridors is to facilitate the development of zero-emission ships. The path to such vessels may include research into various solutions and technologies.

GHG mitigation measures divide into five main categories where the industry should perform research in order to both reduce emissions from ships and also eliminate them. The first category emphasizes hydrodynamic measures, focusing on technology for coating, air lubrication, cleaning, and hull design. Moreover, the second category includes machinery technology and research into how machinery systems can be improved and designed to handle new alternative low and zero-carbon fuels. The third category center around carbon capture and storage technology. In contrast, the fourth category includes research into how one can harvest alternative fuels from the surroundings. The final category emphasizes logistics and digitization measures where vessel speed, ship utilization, fleet size, and alternative routes are relevant areas for research and development. The latter category falls within this thesis.

In order to assess whether this thesis's proposed solution is good, it should compare to the aforementioned alternative measures and technologies. Moreover, investigating when such a solution could be a reality should also be conducted. Energy replenishment is a good solution as it may lead to ripple effects in several other research areas proposed. Almost none of the categories presented can reduce emissions by 100%. The only exception is the implementation of zero-carbon fuels. However, the proposed solution in this thesis arguably combines several of the categories. It is thereby an enabler for reaching zero emissions.

Demonstrating that refueling is possible can also provide better decision support for building ships with alternative fuels. In that way, it will accelerate research and development within both machinery systems and the production and extraction of alternative fuels. Additionally, such a logistical solution can result in new business opportunities arising. For example, new vessel concepts for the distribution and production of fuel can come to life if there is a demand for it. At the same time, it is still debatable whether this thesis's proposed solution will be the most profitable compared to other measures, as many factors come into play for it to succeed.

Chapter 10

Conclusion

This thesis investigates the possibility of replenishing energy at strategic locations along trade lanes to accelerate green shipping corridors. Assessing the value of energy replenishment is accomplished by an optimization model generating the optimal location of energy replenishment points based on a predefined network of locations. The model can identify optimal locations for energy replenishment while simultaneously determining the amount of energy replenished and the required energy storage capacity of the vessels. The model was successfully tested in a case study of the transpacific route between Northeast Asia and the West Coast of the United States, where pure car carriers were selected as the vessel segment to investigate and ammonia as the preferred energy carrier.

The results from the case study illustrate that energy replenishment at strategic locations can be an attractive solution for accelerating the deployment of ammonia-fueled PCC vessels sailing between Northeast Asia and the United States. Our findings discover that refueling at one or more strategic locations along the route will be able to handle the lost opportunity cost for the number of transported cars incurred per cubic meter of ammonia stored in the ship. At the same time, it is also confirmed that underway energy replenishment will lead to reduced required energy storage capacity for the vessels under certain circumstances. However, ammonia-fueled PCC vessels generally require a higher energy storage capacity than corresponding HFO-powered vessels, which is expected. Our results indicate a required energy storage capacity spanning from 2100 m^3 to volumes as high as 11500 m^3. Such numbers are well above the required energy storage capacity of corresponding conventional vessels, where the required storage capacity lies around 2000 to 3000 m^3 depending on the size of the vessel. However, it is also revealed that some of the scenarios reveal a required energy storage capacity that lies close to today's storage capacity of conventional PCC vessels. Based on such a result, it would not be unreasonable to claim that refueling can, under certain conditions, lead to PCC vessels being able to utilize almost the same volumes as they use today for the storage of ammonia in the ship, which in turn can reduce the lost opportunity cost. Simultaneously there is a significant variation in the results, which have its explanation in the input parameters and the selected values. Therefore, further model development should emphasize research into the input parameters and their respective values, but also the actually required volumes for ammonia storage.

Moreover, the results reveal that energy replenishment can occur onshore, offshore, or a combination of these two categories. In scenarios where offshore locations are a part of the optimal solution, dedicated bunkering vessels are assumed to operate out from the fuel hubs strategically located between the continents. Such a solution has yet to be described mathematically in the model and will require further research. A fuel hub in Dutch Harbour and Hawaii is proposed as the only reasonable option without assigning the fuel hubs to either side of the corridor. Establishing fuel hubs in these locations can be critical for a logistical replenishment system in the corridor, after which both hubs are part of the optimal solution in many of the investigated scenarios, either as a direct replenishment location or as a distribution point for ammonia. At the same time, it is revealed that it will be possible to replenish energy offshore without having to depend on bunkering vessels from the proposed fuel hubs, as several scenarios demonstrate success under such circumstances. However, such a solution should only be understood as feasible in a longer time perspective as it will require significant progress on research within offshore fuel production and distribution.

In conclusion, energy replenishment along strategic trade lanes is an attractive solution that can accelerate green shipping corridors. The maritime industry should therefore investigate the concept further. Regardless of the logistical energy replenishment solution proposed in this thesis, North-east Asia - US green corridor must overcome several challenges to succeed. The uptake of ammonia and other alternative fuels, such as hydrogen and methanol, must accelerate, and necessary bunkering infrastructure must be deployed on both sides of the corridor. Additionally, ammonia must be attractive by reducing the current cost gap between the alternative fuel and the conventional alternatives. In closing, a close cross-value chain collaboration between corridor stakeholders in China, South Korea, Japan, and the US will be critical to success. Such collaboration is also true for policy and regulatory incentives between the countries. The US should especially carry a leading role, as most of the geographical land areas in the corridor are under American control.

10.1 Further work

This thesis shows that energy replenishment at strategic locations along the Northeast Asia - US trade route can be a sufficient measure that can accelerate green corridors and the uptake of alternative fuels, collaborative incentives, and technological innovations. Therefore, it is an attractive topic and should be further investigated and compared with other alternative measures.

Several assumptions have been made in the case study to develop a logistical solution for energy replenishment on the Northeast Asia - US green corridor. The model presented in this thesis is relatively general, and it would therefore be attractive to develop the optimization model further to generate an even more realistic picture of how such a logistical solution can unfold. For these reasons, some recommendations for further work are presented.

- Extend the model to include time constraints, which will be necessary to model a more realistic scenario. This will include aspects such as service time at each replenishment location, traveling time between each node, and the maximum duration of a route.

- Further investigate bunkering vessel logistics and how they best can serve offshore replenishment locations. One solution may be to e.g., model the bunkering vessels as a dedicated Vehicle Routing Problem where the fuel hub serves as the depot and a set of offshore locations is to be serviced.

- Investigate alternative strategies for implementing offshore energy replenishment locations. One option is to model offshore replenishment as a grid of points covering the whole corridor with suitable distances between each point in the grid. Such a strategy might be a better option than creating clusters with fewer offshore locations, which is the case in this thesis. A bigger grid of offshore locations might also better illustrate a realistic scenario and the fact that offshore replenishment, in reality, can happen at any point in the pacific ocean.

- Several input parameters in the model are related to high uncertainty. It is especially true for the cost and volume parameters. Therefore, further research should build upon PCC vessels and alternative fuel costs. Additionally, sailing speed, energy consumption, and lost opportunity are recommended for further research as these parameters highly influence the solution and, thereby, the time it will take to distribute cars to the consumer market.

- As an extension of the preceding point, we suggest further investigation into the volume occupied by ammonia fuel tanks and related machinery and safety systems onboard PCC vessels. A significant variation in the required energy storage capacity has been discovered in this thesis, and it is therefore vital to further assess whether such volumes of energy storage, realistically, can be put inside the hull of the PCC vessels.

- Investigate the possibility of extending the corridor by implementing additional ports in Asia, America, and even Central America. Major port hubs such as Hong Kong and Singapore could be included, while ports near the Panama Canal, an essential hub for shipping in general, could also be investigated. Utilizing available AIS data from PCC vessels should serve as decision support for further deployment of ports in the corridor.

- Further investigate the availability of alternative fuels. Alternative fuel options such as methanol and hydrogen could be competitors to ammonia on the transpacific corridor. It is, therefore, reasonable to investigate the potential of such fuels.

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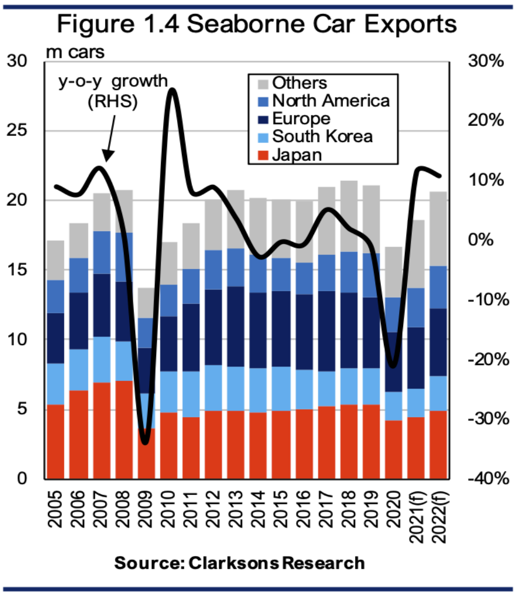
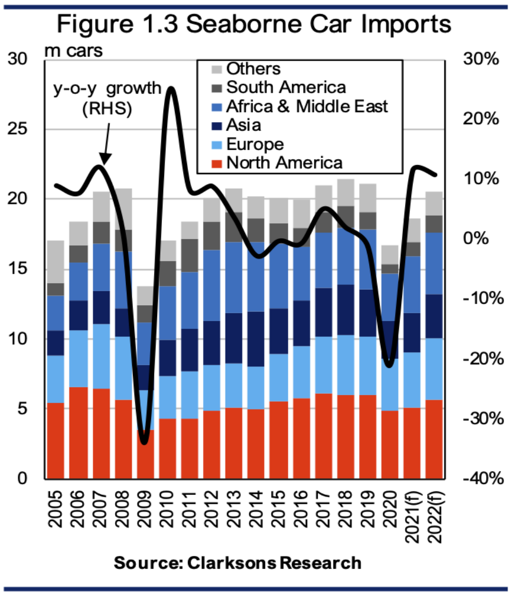
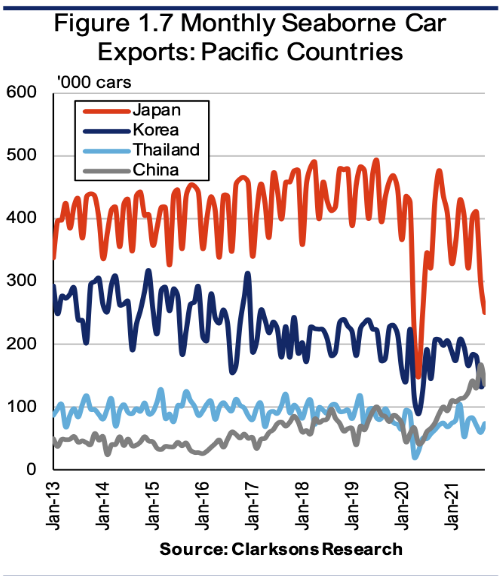
Appendix A

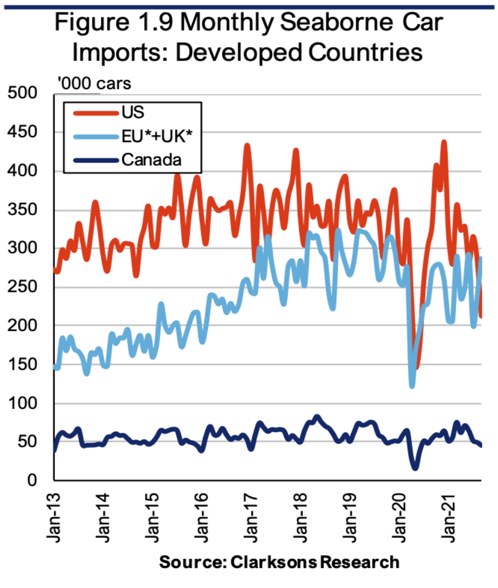
Car Carrier market analysis

A.1 World car export and import by region and countries



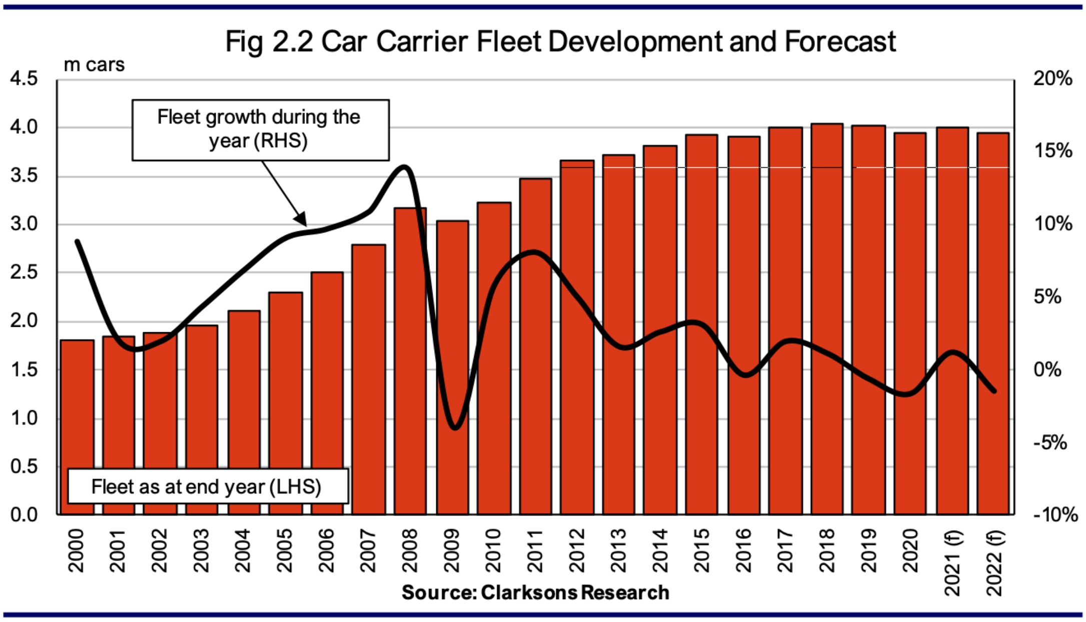






Source: Clarksons Research 2021

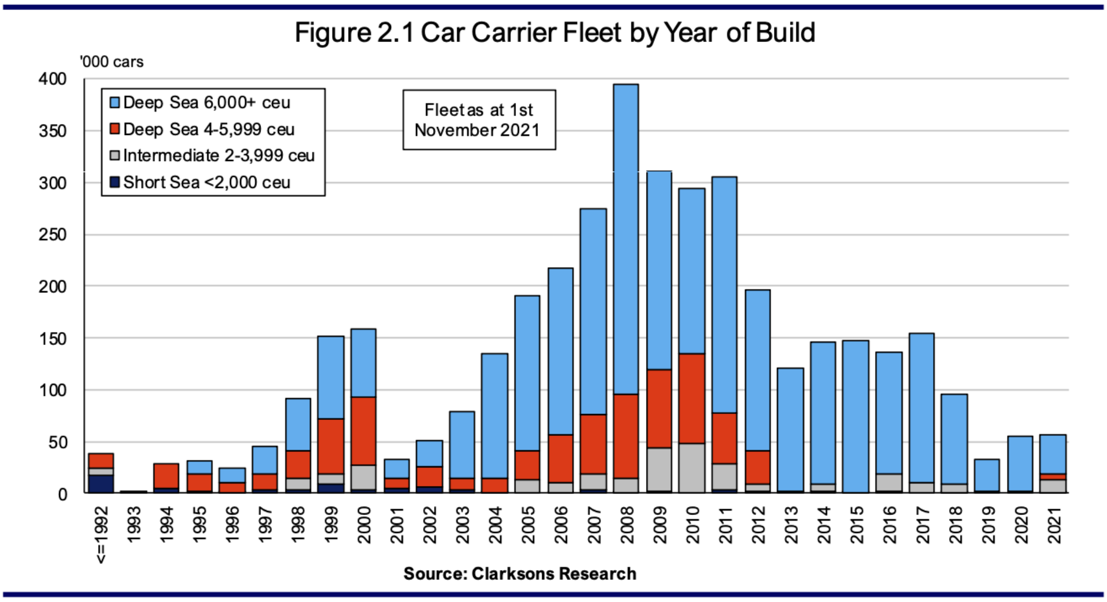
A.2 PCC fleet development



Note: Fleet forecasts are based on projected delivery of the orderbook including expected slippage and cancellation as well as projected demolition volumes. However, no addition is made for future contracting.

Source: Clarksons Research 2021

A.3 PCC fleet by year built



Source: Clarksons Research 2021

A.4 PCC charterers and owners

Figure 3.1 Major Car Carrier Operators By Deployed Fleet

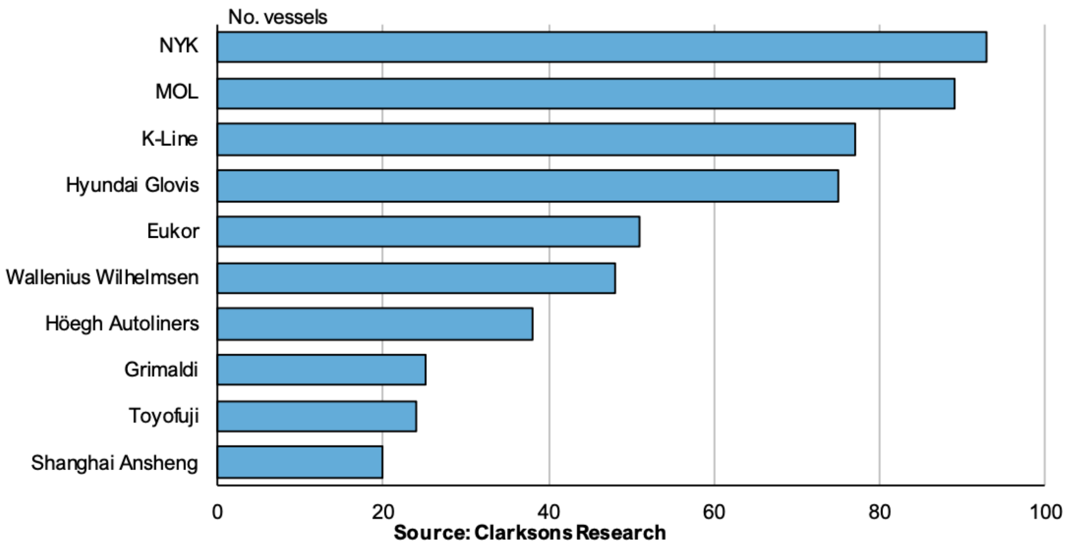
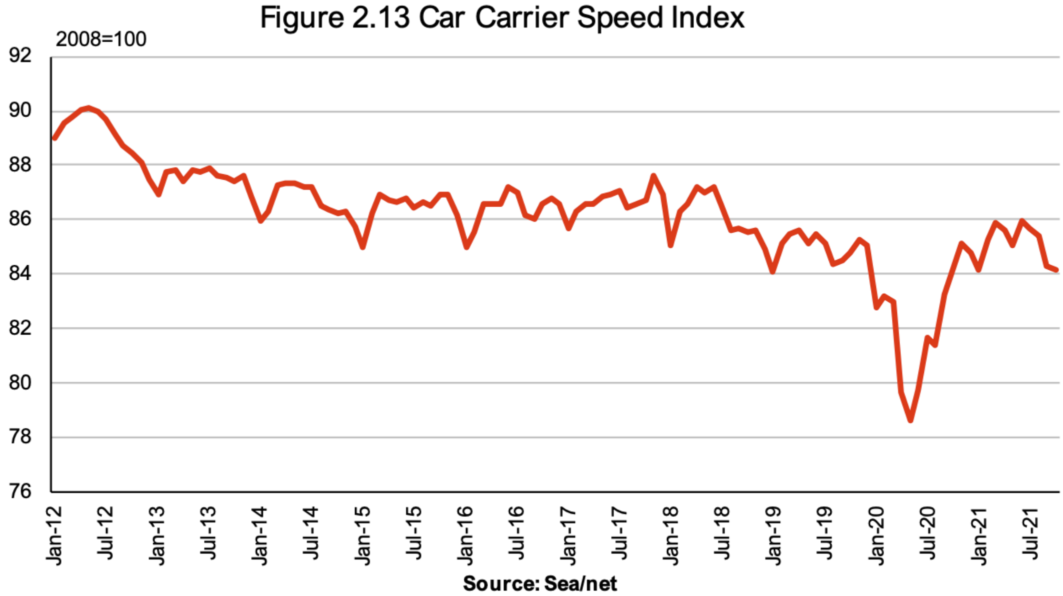


Figure 3.1 shows the approximate operated fleet of selected major car carrier operators as at Q4 2021. Figures include PCCs and PCTCs only, and exclude other units whether Ro-Ro or otherwise.

Source: Clarksons Research 2021

A.5 PCC speed index

Figure 2.13 Car Carrier Speed Index



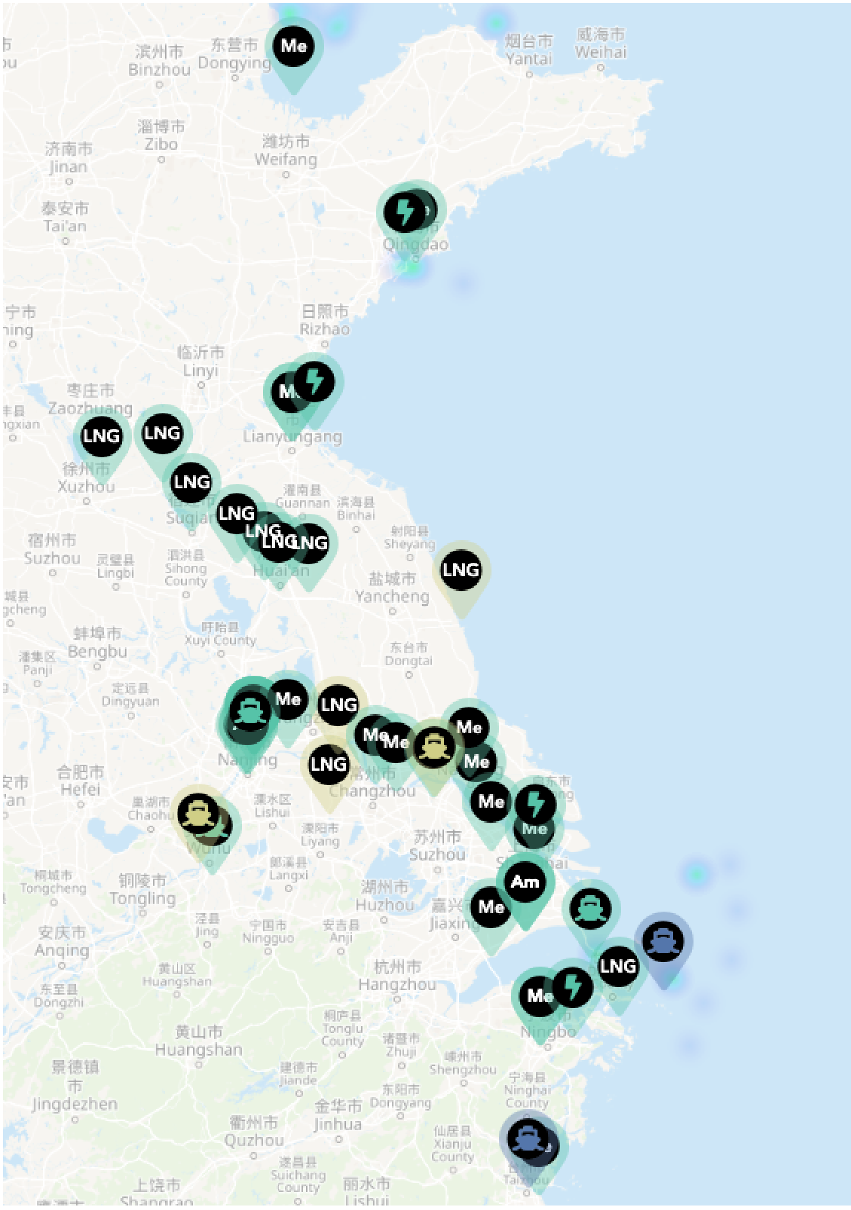
For more details see Sources & Methods for Clarksons Sea/net and Movements Data Aggregate Statistics. A wide range of vessel sector average speed time-series is available on Clarksons Research's Sea/net vessel tracking system.

Source: Clarksons Research 2021

Appendix B

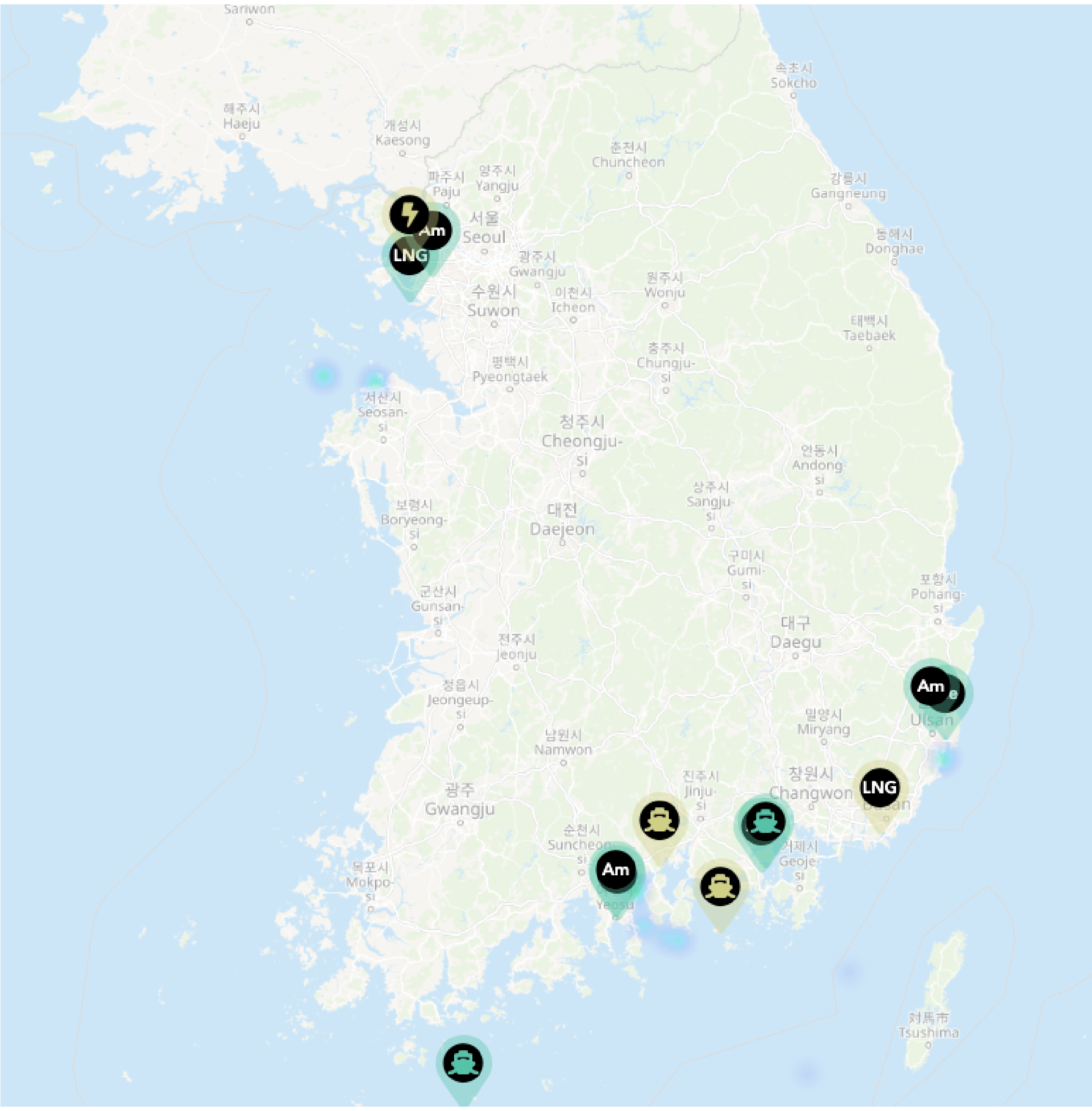
Alternative fuel availability on the Northeast Asia - US corridor

B.1 Alternative fuel availability in China



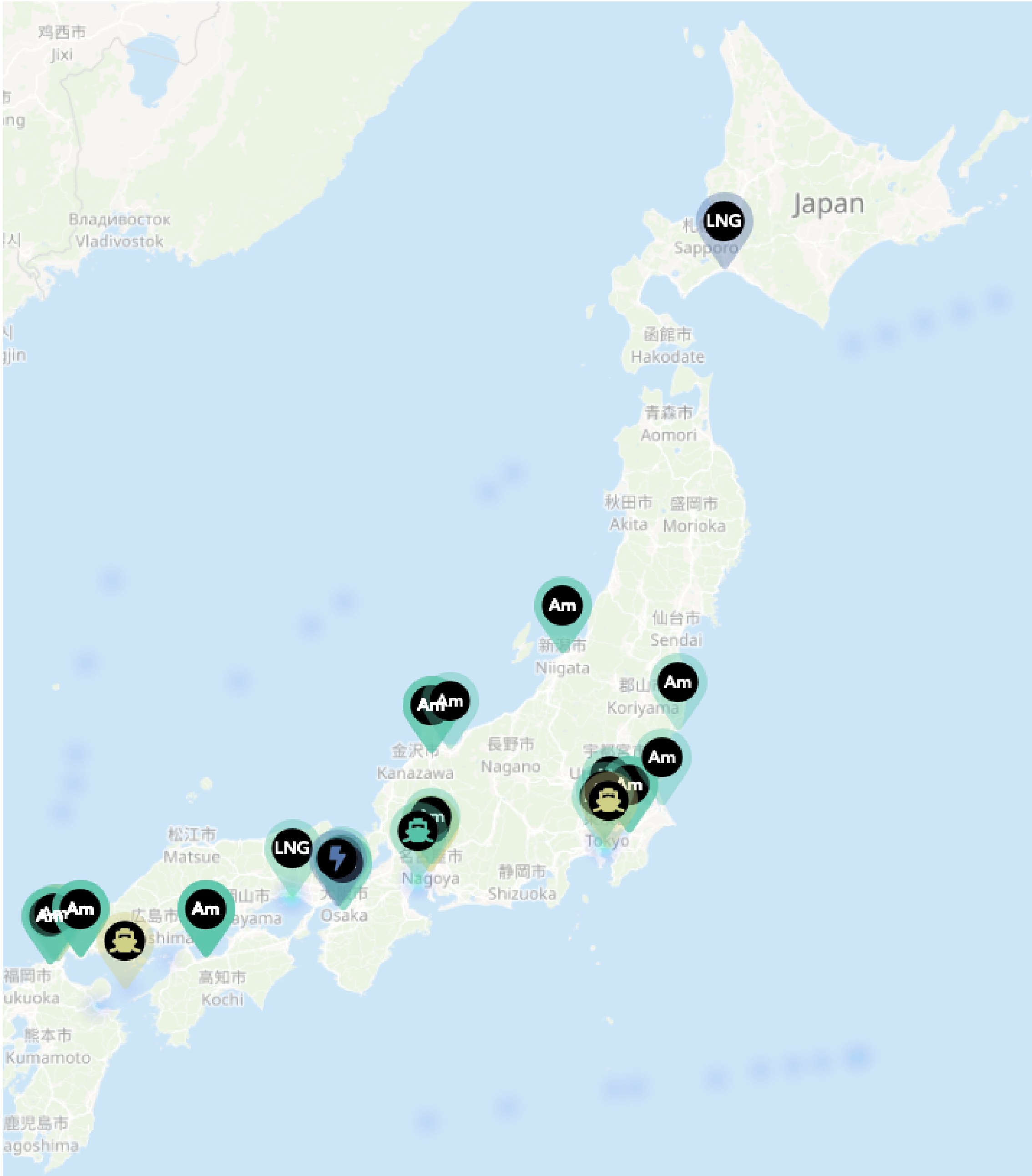
Source: DNV 2023b

B.2 Alternative fuel availability in South Kora



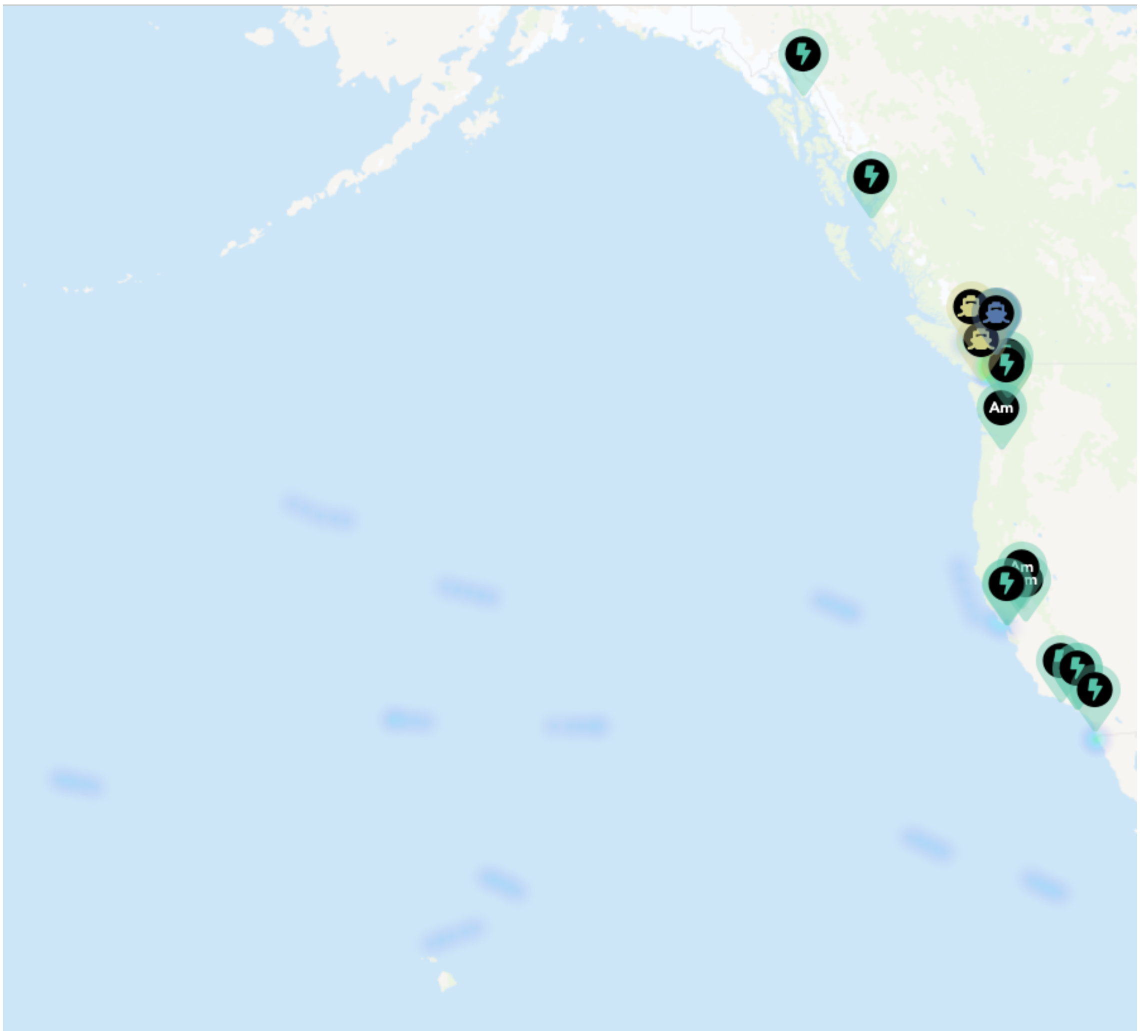
Source: DNV 2023b

B.3 Alternative fuel availability in Japan



Source: DNV 2023b

B.4 Alternative fuel availability on the US west coast



Source: DNV 2023b

Appendix C

Distance matrix

The following appendix displays the sailing distances between all nodes in the case study network, used as input in the mathematical case study model. All distances are provided in nautical miles.

	Shanghai	Pyeongtaek	Nagoya	Tacoma	Portland	Hueneme	Dutch Harbour	Hawaii	RL1	RL2	RL3	RL4	RL5	RL6	RL7	RL8
Shanghai		434.7	792.2	4951.8	5011.4	5583.1	3286	4281.1	2311.4	2567.5	2822.8	3077.1	2225.9	2478.1	2728.9	2978.1
Pyeongtaek	434.7		484.4	4517.1	4576.9	5153.8	2853.7	3946.3	2062.4	2300.0	2539.2	2778.9	1929.6	2169.3	2408.7	2647.3
Nagoya	792.2	484.4		4284.4	4331.5	4856.0	2595.0	3494.1	1578.2	1818.2	2061.4	2306.4	1454.3	1699.9	1945.7	2191.1
Tacoma	4951.8	4517.1	4284.4		113.6	812.6	1690.4	2324.2	3623.9	3421.6	3218.9	3016.6	3426.8	3226.3	3024.4	2821.8
Portland	5011.3	4576.9	4331.5	113.6		706.2	1736.7	2255.9	3620.8	3411.7	3201.9	2992.2	3432.7	3225.7	3017.0	2807.5
Hueneme	5583.1	5153.8	4856.0	812.6	706.2		2304.6	2181.4	3908.5	3666.7	3422.9	3177.4	3773.2	3537.4	3299.0	3058.2
Dutch Harbour	3286.0	2853.7	2595.0	1690.4	1736.7	2304.6		2010.0	2160.4	2038.6	1934.1	1850.2	1901.0	1769.8	1655.7	1562.7
Hawaii	4281.1	3946.3	3494.1	2324.2	2255.9	2181.4	2010.0		2055.2	1783.2	1511.2	1239.9	2066.2	1808.4	1553.4	1303.2
RL1	2311.4	2062.4	1578.2	3623.9	3620.8	3908.5	2160.4	2055.2		272.0	544.0	815.8	300.2	401.1	610.9	852.5
RL2	2567.4	2300.0	1818.2	3421.6	3411.7	3666.7	2038.6	1783.2	272.0		272.0	544.0	401.1	300.2	401.1	610.9
RL3	2822.8	2539.2	2061.4	3218.9	3201.9	3422.9	1934.1	1511.2	544.0	272.0		272.0	610.9	401.1	300.2	401.1
RL4	3077.1	2778.9	2306.4	3016.6	2992.2	3177.4	1850.2	1239.9	815.8	544.0	272.0		852.5	610.9	401.1	300.2
RL5	2225.9	1929.6	1454.3	3426.8	3432.7	3773.2	1901.0	2066.2	300.2	401.1	610.9	852.5		259.9	519.8	779.3
RL6	2478.1	2169.3	1699.9	3226.3	3225.7	3537.4	1769.8	1808.4	401.1	300.2	401.1	610.9	259.9		259.9	519.8
RL7	2728.9	2408.7	1945.7	3024.4	3017.0	3299.0	1655.7	1553.4	610.9	401.1	300.2	401.1	519.8	259.9		259.9
RL8	2978.1	2647.3	2191.1	2821.8	2807.5	3058.2	1562.7	1303.2	852.5	610.9	401.1	300.2	779.3	519.8	259.9	
RL9	2173.1	1832.1	1382.1	3239.8	3255.2	3648.8	1653.8	2114.9	600.4	654.0	793.2	982.2	300.2	392.5	588.2	815.6
RL10	2416.7	2069.0	1624.9	3042.6	3052.0	3421.2	1511.7	1877.5	654.0	600.4	654.0	793.2	392.5	300.2	392.5	588.2
RL11	2658.9	2304.5	1866.7	2843.0	2846.3	3190.7	1385.5	1646.4	793.2	654.0	600.4	654.0	588.2	392.5	300.2	392.5
RL12	2899.3	2538.3	2107.2	2641.8	2638.8	2957.5	1280.6	1425.3	982.2	793.2	654.0	600.4	815.6	588.2	392.5	300.2
RL13	4572.7	4151.6	3823.9	884.2	829.5	1053.4	1363.2	1447.0	2878.5	2648.7	2420.1	2193.5	2726.9	2497.5	2267.6	2037.9
RL14	4369.9	3952.9	3613.3	1074.3	1032.6	1279.8	1213.3	1301.0	2648.7	2420.1	2193.5	1970.5	2497.5	2267.6	2037.9	1809.4
RL15	4162.3	3749.4	3399.1	1271.4	1240.1	1508.6	1079.2	1192.2	2420.1	2193.5	1970.5	1753.2	2267.6	2037.9	1809.4	1583.4
RL16	3950.4	3541.8	3181.7	1472.1	1449.4	1738.5	967.9	1131.7	2193.5	1970.5	1753.2	1544.6	2037.9	1809.4	1583.4	1361.9
RL17	4427.5	3999.1	3703.0	744.9	727.7	1155.9	1159.5	1673.8	2894.4	2683.9	2475.8	2271.7	2713.0	2500.8	2289.5	2080.2
RL18	4238.0	3812.2	3505.0	947.3	937.0	1350.9	995.2	1558.0	2683.9	2475.8	2271.7	2073.4	2500.8	2289.5	2080.2	1874.4
RL19	4043.8	3620.6	3303.6	1150.0	1145.4	1554.2	841.7	1474.6	2475.8	2271.7	2073.4	1883.3	2289.5	2080.2	1874.4	1674.2
RL20	3845.5	3424.9	3099.0	1352.1	1352.7	1762.2	706.7	1429.4	2271.7	2073.4	1883.3	1705.1	2080.2	1874.4	1674.2	1482.6
RL21	4288.2	3855.1	3594.2	711.0	740.8	1318.1	1003.1	1919.4	2933.6	2744.8	2559.8	2380.2	2725.0	2533.5	2344.3	2158.8
RL22	4113.7	3681.8	3411.0	903.7	930.3	1477.9	828.3	1827.5	2744.8	2559.8	2380.2	2208.2	2533.5	2344.3	2158.8	1979.1
RL23	3934.7	3504.2	3224.8	1096.6	1122.3	1650.3	656.3	1762.6	2559.8	2380.2	2208.2	2046.1	2344.3	2158.8	1979.1	1807.4
RL24	3751.9	3322.8	3035.9	1288.9	1315.3	1831.2	491.4	1727.9	2380.2	2208.2	2046.1	1897.2	2158.8	1979.1	1807.4	1647.1

	RL9	RL10	RL11	RL12	RL13	RL14	RL15	RL16	RL17	RL18	RL19	RL20	RL21	RL22	RL23	RL24
Shanghai	2173.1	2416.7	2658.9	2899.3	4572.7	4369.9	4162.3	3950.4	4427.5	4238.0	4043.8	3845.5	4288.2	4113.7	3934.7	3751.9
Pyeongtaek	1832.1	2069.0	2304.5	2538.3	4151.6	3952.9	3749.4	3541.8	3999.1	3812.2	3620.6	3424.9	3855.1	3681.8	3504.2	3322.8
Nagoya	1382.1	1624.9	1866.7	2107.2	3823.9	3613.3	3399.1	3181.7	3703.0	3505.0	3303.6	3099.0	3594.2	3411.0	3224.8	3035.9
Tacoma	3239.8	3042.6	2843.0	2641.8	884.2	1074.3	1271.4	1472.1	744.9	947.3	1150.0	1352.1	711.0	903.7	1096.6	1288.9
Portland	3255.2	3052.0	2846.3	2638.8	829.5	1032.6	1240.1	1449.4	727.7	937.0	1145.4	1352.7	740.8	930.3	1122.3	1315.3
Hueneme	3648.8	3421.2	3190.7	2957.5	1053.4	1279.8	1508.6	1738.5	1155.9	1350.9	1554.2	1762.2	1318.1	1477.9	1650.3	1831.2
Dutch Harbour	1653.8	1511.7	1385.5	1280.6	1363.2	1213.3	1079.2	967.9	1159.5	995.2	841.7	706.7	1003.1	828.3	656.3	491.4
Hawaii	2114.9	1877.5	1646.4	1425.3	1447.0	1301.0	1192.2	1131.7	1673.8	1558.0	1474.6	1429.4	1919.4	1827.5	1762.6	1727.9
RL1	600.4	654.0	793.2	982.2	2878.5	2648.7	2420.1	2193.5	2894.4	2683.9	2475.8	2271.7	2933.6	2744.8	2559.8	2380.2
RL2	654.0	600.4	654.0	793.2	2648.7	2420.1	2193.5	1970.5	2683.9	2475.8	2271.7	2073.4	2744.8	2559.8	2380.2	2208.2
RL3	793.2	654.0	600.4	654.0	2420.1	2193.5	1970.5	1753.2	2475.8	2271.7	2073.4	1883.3	2559.8	2380.2	2208.2	2046.1
RL4	982.2	793.2	654.0	600.4	2193.5	1970.5	1753.2	1544.6	2271.7	2073.4	1883.3	1705.1	2380.2	2208.2	2046.1	1897.2
RL5	300.2	392.5	588.2	815.6	2726.9	2497.5	2267.6	2037.9	2713.0	2500.8	2289.5	2080.2	2725.0	2533.5	2344.3	2158.8
RL6	392.5	300.2	392.5	588.2	2497.5	2267.6	2037.9	1809.4	2500.8	2289.5	2080.2	1874.4	2533.5	2344.3	2158.8	1979.1
RL7	588.2	392.5	300.2	392.5	2267.6	2037.9	1809.4	1583.4	2289.5	2080.2	1874.4	1674.2	2344.3	2158.8	1979.1	1807.4
RL8	815.6	588.2	392.5	300.2	2037.9	1809.4	1583.4	1361.9	2080.2	1874.4	1674.2	1482.6	2158.8	1979.1	1807.4	1647.1
RL9		245.8	491.6	737.0	2595.5	2369.3	2141.5	1912.5	2548.9	2337.4	2125.2	1913.1	2530.6	2337.7	2145.6	1955.4
RL10	245.8		245.8	491.6	2369.3	2141.5	1912.5	1682.8	2337.4	2125.2	1913.1	1702.2	2337.7	2145.6	1955.4	1768.7
RL11	491.6	245.8		245.8	2141.5	1912.5	1682.8	1452.9	2125.2	1913.1	1702.2	1493.6	2145.6	1955.4	1768.7	1587.6
RL12	737.0	491.6	245.8		1912.5	1682.8	1452.9	1223.6	1913.1	1702.2	1493.6	1289.7	1955.4	1768.7	1587.6	1414.9
RL13	2595.5	2369.3	2141.5	1912.5		229.9	459.6	689.0	300.2	372.8	534.2	727.2	600.4	636.4	733.9	872.2
RL14	2369.3	2141.5	1912.5	1682.8	229.9		229.9	459.6	689.0	300.2	372.8	534.2	727.2	600.4	733.9	872.2
RL15	2141.5	1912.5	1682.8	1452.9	459.6	229.9		229.9	534.2	372.8	300.2	372.8	733.9	636.4	600.4	636.4
RL16	1912.5	1682.8	1452.9	1223.6	689.0	459.6	229.9		727.2	534.2	372.8	300.2	872.2	733.9	636.4	600.4
RL17	2548.9	2337.4	2125.2	1913.1	300.2	372.8	534.2	727.2		212.2	424.2	635.9	300.2	362.1	503.9	676.8
RL18	2337.4	2125.2	1913.1	1702.2	372.8	300.2	372.8	534.2	212.2		212.2	424.2	362.1	300.2	362.1	503.9
RL19	2125.2	1913.1	1702.2	1493.6	534.2	372.8	300.2	372.8	424.2	212.2		212.2	503.9	362.1	300.2	362.1
RL20	1913.1	1702.2	1493.6	1289.7	727.2	534.2	372.8	300.2	635.9	424.2	212.2		676.8	503.9	362.1	300.2
RL21	2530.6	2337.7	2145.6	1955.4	600.4	636.4	733.9	872.2	300.2	362.1	503.9	676.8		192.9	385.6	577.9
RL22	2337.7	2145.6	1955.4	1768.7	636.4	600.4	636.4	733.9	362.1	300.2	362.1	503.9	192.9		192.9	385.6
RL23	2145.6	1955.4	1768.7	1587.6	733.9	636.4	600.4	636.4	503.9	362.1	300.2	362.1	385.6	192.9		192.9
RL24	1955.4	1768.7	1587.6	1414.9	872.2	733.9	636.4	600.4	676.8	503.9	362.1	300.2	577.9	385.6	192.9	

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