Master's thesis

NTNU
Norwegian University of Science and Technology
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Optimal Location of Energy Replenishment Stations for Zero-Emission Vessels

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2022

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Master`s Thesis in Marine Systems Design
Stud. techn. Eirik Eikeland Haahjem
"Optimal Location of Energy Replenishment Stations for Zero-Emission Vessels"
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Background
To enable the green shift within marine transportation new energy carriers needs to be adopted by the industry. Many of the zero-emission energy carriers have challenges when it comes to energy storage capacity. To make zero-emission energy carriers competitive new investments in energy replenishment infrastructure can prove important.

Overall aim and focus
The overall aim of the master thesis is to develop an optimization model for decision support for the optimal placement of energy replenishment stations.

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

1. *Provide an overview of relevant technologies and trends within zero-emission energy carriers for marine purposes and related concepts.*
2. *Develop a mathematical optimization model for the optimal placement of energy replenishment stations.*
3. *Expand the model and carry out a case study where energy replenishment stations may become an alternative.*
4. *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 Project work.

Stein Ove Erikstad
Professor/Responsible Advisor

Preface

This master's thesis concludes my Master of Science Degree at the Department of Marine Technology at NTNU and it corresponds to a workload of 30 ECTS. The work performed in this thesis is a continuation of my project thesis.

I would like to give a special thank you to my supervisor Professor Stein Ove Erikstad, for guidance and feedback during the work with the thesis. I also enjoyed professional discussions with my fellow students.

Eirik Eikeland Haahjem
Trondheim, Norway
June 11, 2022

Abstract

To enable the green shift within marine transportation zero-emission energy carriers need to be adopted by the industry. A considerable challenge for some of the zero-emission energy carriers (e.g hydrogen) is energy storage capacity. To make zero-emission energy carriers competitive new investments in energy replenishment infrastructure can prove important. In this master's thesis the aim is to develop a decision support tool in the form of a mathematical model to identify the optimal location for energy replenishment stations to serve zero-emission vessels. The maritime container traffic between North-America and West-Europe is used as a case study with liquid hydrogen as energy carrier.

Giving foundation to the development of the mathematical model efforts have been put into presenting the available and soon to be available zero-emission energy carriers and their properties, furthermore concepts regarding energy replenishment from offshore infrastructure and general zero-emission targets within the maritime industry are presented.

The mathematical model is develop step-by-step with iterative model expansions. Starting with a simple model similar to a facility location problem model and ending up with a final model which solve the transatlantic energy replenishment station location case. The results show that liquid hydrogen powered vessels will require energy replenishment stations, moreover they need additional energy storage capacity compared to a conventional vessel of the same size.

Energy replenishment stations for zero-emission vessels represents one of many possibly enabling solutions for the green shift within maritime transportation. The tempo in which this transition needs to be done highlights the importance of research done to facilitate for good decision support on the area.

Sammendrag

For å muliggjøre det grønne skiftet innen sjøtransport, så må nullutslippsenergibærere tas i bruk av industrien. En betydelig utfordring for noen av nullutslippsenergibærerne (f.eks. hydrogen) er energilagringskapasitet. For å gjøre nullutslippsenergibærere konkurransedyktige kan nye investeringer i energipåfyllingsinfrastruktur vise seg å være viktig. I denne masteroppgaven er målet å utvikle et beslutningsstøtteverktøy i form av en matematisk modell for å identifisere den optimale plasseringen for energipåfyllingsstasjoner for å betjene nullutslippsfartøy. Den maritime containertrafikken mellom Nord-Amerika og Vest-Europa brukes i en casestudie med flytende hydrogen som energibærer.

For å legge grunnlaget for utviklingen av den matematiske modellen er det gitt fokus til å presentere tilgjengelige og snart tilgjengelige nullutslippsenergibærere og deres egenskaper. Videre er konsepter relatert til energipåfyll fra offshore-infrastruktur og generelle nullutslippsmål innen den maritime industrien presentert.

Den matematiske modellen utvikles trinn for trinn med iterative modellutvidelser. Den starter med en enkel modell som ligner på en formulering for optimal lokalisering et annlegg (FLP)og ender opp med en endelig modell som løser problemet med lokalisering av transatlantiske energipåfyllingsstasjoner. Resultatene viser at flytende hydrogen-drevne fartøy vil kreve energipåfyllingsstasjoner og dessuten ekstra energilagringskapasitet enn det som kan forventes av et konvensjonelt fartøy av samme størrelse.

Energipåfyllingsstasjoner for nullutslippsfartøy representerer en av mange mulige muliggjørende løsninger for det grønne skiftet innen sjøtransport. Tempoet denne overgangen må gjøres i, understreker viktigheten av forskning som gjøres for å legge til rette for god beslutningsstøtte på området.

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Acronyms

IMO	International Maritime Organization
GHG	Greenhouse Gas
ICS	International Chamber of Shipping
EEDI	Energy Efficiency Index
LNG	Liquid Natural Gas
IAE	International Energy Agency
ICE	Internal Combustion Engine
FC	Fuel Cell
TTS	Truck-to-Ship
PTS	Port-to-Ship
STS	Ship-to-Ship
UREP	Underway Replenishment
FOWT	Floating Offshore Wind Turbine
FPSO	Floating Production, Storage and Offloading
OR	Operation Research
FLP	Facility Location Problem
FBX	Freightos Baltic Index

Chapter 1

Introduction

There is an increased pressure to abandon carbon-intensive fuels and comply with the global goals to combat climate change, and the maritime industry stands before important decisions. The most promising energy carriers have drawbacks compared to existing carbon-based fuels, mainly related to volumetric density and more complicated handling and storage solutions. Depending on the adopted solutions new infrastructure needs to be put in place to serve the world fleet of zero-emission vessels.

1.1 Transition away from fossil fuels

In the wake of the Paris agreement of 2015 [1] where the goal of keeping the global temperature increase from pre-industrial levels well below 2°C and preferably below 1.5°C, the International Maritime Organization (IMO) made their own targets for the international shipping industry which was not directly targeted by the Paris agreement. In 2018 three main levels of ambition where stated by IMO in the initial IMO greenhouse gas strategy[2].

- The first ambition level is to lower the carbon intensity of ships by strengthening the energy efficiency design index (EEDI) for new ships.
- The second ambition level sets declining targets for the carbon intensity of international shipping. With specific goals to reduce CO2 emissions per transport work by at least 40 % by 2030, and pushing efforts towards 70 % by 2050, compared to 2008.
- The third ambition level seeks for the total Greenhouse gas (GHG)emissions from shipping to peak and decline as soon as possible and reduce by at least 50 % by 2050 compared to 2008 ("50 by 2050" has been a slogan in the shipping industry).

Only a few years later these goals seem outdated compared to the global goal of reaching a net zero in 2050. This mentality is underlined by the international chamber of shipping (ICS) representing the national shipowner associations and over 80 % of the global shipping fleet. They support the 2050 net zero goal and have stated they will push to get it implemented in IMO framework. According to the ICS many of the vessels being commissioned by 2030 need to be based on zero-emission technology to reach that goal[3].

1.2 The global shipping traffic

The marine shipping sector today accounts for about 3% of global GHG emissions and marine shipping accounts for about 9% of the global emissions related to transportation. Nevertheless with 80-90% of global trade being enabled by ships it is a energy efficient way of transporting goods compared to other available means. There has been a continued growth in the international fleet for the last decades with an average annual growth rate of about 2.5% between 2013 and 2018. The general trend is that the vessels being built now are continuously getting larger. The larger vessels experiencing annual growth rates of above 25% and accounts for about 85 % of the GHG emissions from the shipping industry [4].

1.3 The purpose and motivation

This master's thesis aims to provide decision support for the location of future energy replenishment stations for zero-emission vessels. To accelerate the green shift within the marine transportation industry relevant stakeholders need to investigate multiple options for making the transition as smooth as possible, the energy replenishment stations being one such alternative.

1.4 Objectives

As stated in the master thesis description, the following objectives should be pursued:

1. Provide an overview of relevant technologies and trends within zero-emission energy carriers for marine purposes and related concepts.
2. Develop a mathematical optimization model for the optimal placement of energy replenishment stations.
3. Expand the model and carry out a case study where energy replenishment stations may become an alternative.
4. Discuss and conclude.

1.5 Scope and limitation

As stated in the the enclosed master thesis description, the work in this thesis is concentrated around developing a mathematical optimization model to give decision support for the location of energy replenishment stations for zero-emission vessels.

The feasibility of technical solutions to make energy replenishment operations offshore possible have not been part of this study.

1.6 The structure of the report

The thesis is organized in the following way::

- **Chapter 2:** Provides the reader with a background to the main drivers for zero-emission vessels and the concept of green corridors. It also briefly discusses potential energy carries, energy replenishment methods and concepts for ships.
- **Chapter 3:** Gives an introduction to methods within operation research important for this thesis and a literature review of similar applications.
- **Chapter 4:** Presents the development and behaviour of a mathematical optimization model to solve optimal energy replenishment station location.
- **Chapter 5:** Introduces the case of the transatlantic container traffic to which the model developed in Chapter 4 is further expanded to handle. Furthermore, an version of the case is solved.
- **Chapter 6:** Contains critical assessment and discussion of the work and results.
- **Chapter 7:** Provides the conclusion and suggestions for further work.

Chapter 2

Background

In this chapter the background for some of the main considerations made when selecting the optimal location of energy replenishment stations will be presented. Where hydrogen and hydrogen related technology is given the most focus.

2.1 Green corridors

Adapting zero-emission technologies for ships involves a higher technological risk for the stakeholders compared to conventional fossil fuel technology. The capital cost of available and soon to be available zero-emission vessels are also magnitudes larger at the moment. To accelerate the zero-emission transition the playing field needs to be leveled. One alternative is the introduction of "green corridors": specific trade routes between major port hubs with zero emission solutions. The goal of green corridors is to enable sustainable green solutions and enhance the competitiveness of the logistics industry. Making available the infrastructure needed for the green solutions while also complementing with favourable regulatory framework green corridors can provide long-term and large-scale logistics answer[5]. The initiatives for green corridors can be summarized in Figure 2.1. The policies and regulations supports the three main categories of projects. The corridors are geographically defined connections between nodes to which the infrastructure must support efficiently. Different modes of transport and loading/unloading are handled by transport techniques and finally complete business solutions creates the value chains connecting to complete logistics solutions.

In the aftermath of the UN climate change conference (COP 26) many of the leading shipping nations signed the Clydebank declaration for zero-emission maritime routes between 2 (or more) ports[6]. A Nordic initiative has recently been announced to establish specific routes that can only be serviced by zero-emission vessels for the many trading and ferry routes connecting the countries[7]. Many of these projects are feasible now or in the near future. The distance between energy replenishment for the zero-emission concepts is often an important supplier of conditions for the solution and deep sea shipping routes are a major challenge.

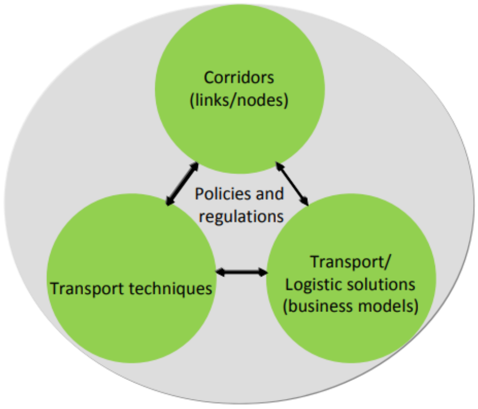


Figure 2.1: The underlying concept of green corridors[5]

The importance of decarbonising these routes are nevertheless important if the global goals of decarbonization by 2050 are to be reached. The choice of the first green corridors for deep sea shipping will be decisive and provide foundation for investment confidence for stakeholders. The Australia-Japan iron-ore route and the Asia-Europe container route have been identified by a McKinzey sustainability report as potential green corridors on the basis of four selection criteria much like Figure 2.1. Stakeholders that are prepared to collaborate across the supply chains with a firm commitment to decarbonization, a viable energy carrier to power the vessels, a demand from end consumer for green transportation of products and finally policy and regulations to accelerate and support the solutions[8].

2.2 Marine energy carriers

In this section some of the most promising energy carriers and their characteristics will be presented. The energy carriers used in the shipping industry needs to be available, cost-efficient, compatible with infrastructure and compliant with current and future environmental requirements. Today the dominant marine energy carriers are carbon-based. Among these heavy fuel oil, light fuel oil and marine diesel oil are the most used[9]. In recent years liquid natural gas (LNG) has been given increased attention as a transitional fuel, however it remains a transitional fuel and other energy carriers needs to be considered as long term solutions.

To meet the zero-emission targets, fossil fuels needs to be replaced by green alternatives. In international shipping virtually no low-carbon fuels have been adopted to date. Biofuels are currently the only example that can be considered green and they only stand for about 0.1% of total energy consumption [10]. One of the main challenges with further upscale of biofuels usage is related to the limited sustainable production capacity. Biofuels are therefore seen to have a limited potential as a marine fuel. All electric battery powered vessels have already proven themselves on shorter sea routes however they are not well suited for deep sea shipping because of their relatively low volumetric- (and gravimetric-) energy density. Hydrogen and hydrogen-based fuels such as ammonia and methanol are seen as the most promising alternatives for the zero-emission future of international shipping. Nevertheless there are various technical obstacles that needs to be handled before they become a more relevant choice for the shipowners.

The energy carriers have different requirements for storage. In Table 2.1 the storage pressure, volumetric energy density and corresponding temperature is listed for some of them. The challenge to find attractive storage solutions for marine purposes is specially true for energy carriers stored under high pressure or very low temperature due to complexity and space occupation of the storage systems.

Fuel type	Volumetric energy density (GJ/m^3)	Storage pressure (Bar)	Storage temperature (°C)
Marine gas oil	36.6	1	20
Liquid natural gas	23.4	1	-162
Methanol	15.8	1	20
Liquid ammonia	12.7	1/8,6	-34/20
Liquid hydrogen	8.5	1	-234
Compressed hydrogen	7.5	700	20

Table 2.1: Storage properties of different marine fuels [11]

2.2.1 Hydrogen

Hydrogen is one of the fuels competing to become the dominating solution to the problem of transitioning away from carbon intensive fuels. The main reason being that it can be generated through the use of electricity from renewable resources.

Hydrogen production

The global hydrogen demand of 2020 was dominated by oil refining industry applications. In the international energy agency (IEA) Net Zero Scenario, the global hydrogen demand is projected to more than double by 2030 [12]. This is driven mainly by electric grid balancing use and hydrogen based fuel demand e.g. liquid hydrogen, ammonia and other synthetic fuel types. Hydrogen is categorized into colours by the method it is produced. The four most common are:

- Green - hydrogen produced through electrolysis with electricity generated from renewable resources.
- Blue - hydrogen produced from natural gas and the carbon-emissions related to the process are captured and stored.
- Grey - hydrogen is produced from natural gas, but emissions are not captured.
- Brown - hydrogen produced form coal, but emissions are not captured.

The by far most common way of producing hydrogen today is by the use of the process called steam reforming leading to grey hydrogen [13]. This leads to a great deal of GHG emissions and for hydrogen to become a zero emission alternative the production must be based on a green or blue hydrogen pathway.

Hydrogen storage

Hydrogen storage is a challenge both in terms of space occupancy, complexity and safety. The systems needed to keep hydrogen at low enough temperatures or at to stay liquid or at high enough pressure are very complex compared to conventional fuel. Hydrogen also has a safety aspect that must be handled related to its high flammability. Due to the low volumetric energy density achievable deep sea application is seen as difficult.

Hydrogen consumption

There exists two main options for utilizing hydrogen. They can be applied in Internal combustion engine (ICE) or in fuel cell (FC). Using hydrogen in combination with other fuels in ICE is also an option. With FC or hydrogen-fuelled ICE the only end product when using hydrogen would be water and electrical energy.

2.2.2 Green ammonia

In recent years ammonia(NH_3) has been getting more support as the fuel for the future of international shipping[10][14]. The main advantages of Ammonia compared to hydrogen is the less complex storage systems required and the relatively higher volumetric energy density affecting the suitability for deep sea applications.

Ammonia production

Green Ammonia or E-ammonia refers to ammonia made from an electrochemical process, where green hydrogen and nitrogen captured with the use of electricity (also from renewable resources) are combined to form ammonia through the Harber-Bosch process.

Ammonia storage

Ammonia is highly toxic and must be handled with care for both crew and environment, nevertheless ammonia is a commodity widely traded for within the fertilizing industry meaning that there exist competence and experience on handling these issues. It is also less complicated to transport ammonia compared to hydrogen as it can be stored as a liquid at temperatures around -34°C.

Ammonia consumption

Ammonia is considered both for uses in a combustion engines as well as fuel cells. The technology however needs to mature for it to be a viable option [14]. Several engine manufactures are developing new engine technology and it is expected that ammonia powered vessels will become available soon. To underline the prospects of ammonia many of the shipowners today order ammonia ready vessels.

2.2.3 Other e-fuels

In addition to ammonia, other e-fuels based on renewable hydrogen are considered for the future of shipping. E-methanol, e-methane and e-diesel are mentioned as candidates. They all rely on green hydrogen in a synthesis with carbon monoxide for the case of e-methanol and carbon dioxide for e-methane and e-diesel. A disadvantage for these fuels compared to hydrogen and ammonia is their content of carbon. To become carbon neutral alternatives they all need direct air captured CO_2 in the production. The production of methanol by CO_2 is specially energy demanding due to the chemical bonds in the molecule. The majority of methanol produced today is made by combining carbon monoxide derived from natural gas or coal with hydrogen[15]. Carbon neutrality could also be achieved by introducing carbon capture at the point of consumption.

A factor speaking for the commitment towards these fuels is their compatibility with existing technology. They also score relatively high on volumetric density compared with hydrogen and ammonia.

2.2.4 Nuclear

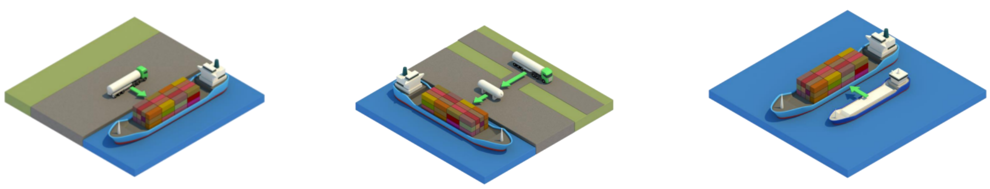
Nuclear propulsion comes with some great advantages compared to conventional fuel. A nuclear reactor does not emit greenhouse gases. Compared to the space for engine, exhaust system, fuel tanks, etc for vessel running on conventional fuel, the nuclear reactor can be relatively compact. Depending on the nuclear fuel type, enrichment and reactor type the intervals between refueling can be from a few months to a few years. There are four main fuels for a nuclear reactor for maritime purposes Uranium, Plutonium, Thorium and mixed oxide fuel[16]. The fuel cost is low compared to conventional fuel and the cost related to high speed operations for a conventionally fueled ship does not apply, however the investment cost required for a nuclear powered vessel can be as much as 2.5-3 times that of a conventional vessel [17]. Previous commercial nuclear vessels have not been allowed to visit some ports because of nuclear risk, limiting their route options. The decommissioning and nuclear waste management is also a demanding barrier. Nuclear reactors used to power ships have therefore as a consequence mainly been reserved for naval vessels such as aircraft carriers and submarines.

2.2.5 Battery

Battery for maritime applications is not a new phenomenon with small passenger ferries operating in Norway at the end of the 19th century [18]. Technology advances within battery technology has given vessels relying solely on batteries again increased attention. All-electric car ferries have already been operating for a few years in Norway. If receiving electricity from renewable resources the batteries gives a zero-emitting option for vessel owners. As a way of increasing propulsion system efficiency vessels are now being constructed with electricity as the main energy vector[19]. This facilitates a hybrid system with the use of electricity storage solutions such as batteries, fly wheels and supercapacitors. The achievable energy density, power density and usable lifetime are factors limiting the applicable area for all electric battery powered vessels. A downside of using battery as the source of electrical energy is the charging time between of cycle although concepts are being developed for battery swapping mitigating the issue.

2.3 Energy replenishment for ships today

The need for energy replenishment of ships emerged with the introduction of the steam engine running on coal fired boilers and has developed since. The naval powers at the time placed coaling- or fueling stations at strategic locations maximizing the operational range for the naval warships. The nature of the refueling operation or energy replenishment depends on the fuel, the size of the ship and the area of operation. Today the merchant fleet rely mainly on large refueling hubs along the most trafficked routes and close to the busiest ports. Vessels in liner traffic usually have a refueling strategy based on a few pre-selected ports that they engage with long term contracts. Bunkering is most commonly done by Truck-to-Ship (TTS), Ship-to-Ship (STS) and Terminal(Port)-to-Ship (PTS) illustrated in Figure 2.2 [20].



(a) Truck-to-Ship (TTS) **(b)** Port-to-Ship (PTS) **(c)** Ship-to-Ship (STS)

Figure 2.2: Most common bunkering operations[21]

Truck-to-Ship

TTS bunkering is done by transferring fuel to a vessel moored at the dock or a jetty, from a truck connected by a flexible hose. This way of bunkering give flexibility to vessel operators and port authorities. The flexibility comes at the expense of lower fuel transfer capacity and potentially increased risk of accidents due to variations in locations and procedures.

Port-to-ship

In PTS-bunkering the vessel visits a fixed bunkering installation with a capacity that normally can fit the needs of more vessels. The vessels visiting such locations need to deviate from their route to get to the terminals. The transfer rate of fuel is higher so for larger vessels the duration can be much shorter compared with TTS-bunkering. The safety will normally be higher since it is more of a routine operation for both crew and facilitators.

Ship-To Ship

Using a dedicated ship or barge for refueling as in STS-bunkering the vessel-operator is given the possibility to not enter a port solely to refuel. It also offers the same type of benefits with regards to flow rate and capacity as when done in port. The main downside with this option is the high capital cost of having a dedicated bunkering vessel. The operation can also be considered as more prone to accidents compared to PTS.

Underway replenishment

Underway replenishment (UREP) can be seen as a variant of STS bunkering operation. Keeping the naval vessels in combat ready locations gave rise to UREP of vessels at sea. This operation allowed their vessels to prolong their capabilities at sea indefinitely. The use of UREP for ships in commercial traffic is not widespread because of the high capital and operational costs of having a designated refueling vessel in remote locations compared to the cost of increasing fuel capacity to be able to reach the next fuel hub. For vessels relying on energy carriers with low volumetric density more flexible replenishment operations may be prove important.

2.4 Offshore energy replenishment for zero-emission vessels

This section seeks give an introduction to offshore energy replenishment and why it can become important in a zero-emission scenario. With the increase in offshore energy generation in the last decade and the projected development within the industry new opportunities arise for offshore energy replenishment for ships in connection with these facilities. By placing offshore wind turbines and other power generating units such as solar further offshore good options for energy storage, conversion and transportation becomes important.

2.4.1 Need for offshore energy replenishment

The introduction of zero-emission technology for vessels discussed in section 2.2 will in most instances result in reduction of operational range for the vessel. For the zero-emission vessels to be able to fulfill the same demand as vessels relying on carbon-based fuel adjustments in operational pattern, infrastructure and/or fleet size must be made. Zero-emission vessels with a shorter range than conventionally powered vessels may make good use of power replenishment en route to the port of destination. Establishing power replenishment stations in connection to heavily trafficked routes with a demand supporting large investments could contribute to making zero-emission vessels compatible with previously unsuitable routes. For zero-emission vessels servicing routes close to ports or shorter routes at open sea the value of having a designated energy replenishment station may be limited.

2.4.2 Offshore energy hubs

An offshore energy hub can be defined as a hub where energy conversion, storage and distribution can take place. Renewable resources such as offshore wind and solar energy generate a fluctuating power supply to the grid which is not always "in sync" with the demand of the end users. As electricity must be consumed when generated solutions for storage of power becomes ever more important. Batteries and e-fuels can play important roles to balance the grid. This can also be an opportunity for future zero-emission vessels. A survey answered by a range of industry- and academic actors suggest that energy replenishment for battery electric- or fuel cell powered vessels at wind farms will be commercially available by 2028[22].

In a study by Thommessen *et al.* [23] an offshore energy hub serving the growing offshore wind farms is studied. The hub is to supply the onshore grid while also potentially converting electricity to e-fuels such as hydrogen and ammonia. Through a techno-economic feasibility analysis on three alternative scenarios the researchers conclude that the technical aspect is covered with similar projects in other environments already operating, but that the economical side must improve for it to become viable. In the first scenario the power generated by the wind turbines is directly supplied to the grid. The other two scenarios involve production, storage, transport or electricity re-generation by fuel cells of hydrogen and ammonia respectively.

2.4.3 Conceptual offshore energy replenishment options

In this section some of the conceptual ideas and projects for energy replenishment offshore are presented. With hydrogen based or pure electric powered vessels new challenges as well as new opportunities emerge in the planning of energy replenishment-locations and -station concepts. The bunkering infrastructure today is based upon the demand for carbon based fuels in the large shipping hubs of the world. Renewable energy generation offshore may pave way for a more decentralized energy replenishment service given that a variety of e-fuels can be fabricated without supply of additional raw materials.

Offshore e-fuel production and bunkering facility

Floating offshore wind turbines (FOWT) are seen as one of the enablers of the green shift with over 80 % of the offshore wind resources located at depths bellow 60m[24]. There are multiple examples of planned hydrogen offshore production facilities in connection to offshore wind farms such as Denmark's wind energy hub [25] and ERM's Dolphyn project seen in Figure 2.3. Common for both concepts is that they plan to produce hydrogen from wind energy and distilled seawater close to the wind farms. The offshore production of hydrogen does not only need to be dependent of FOWT, but could also be produced by other means of renewable power generation such as solar.

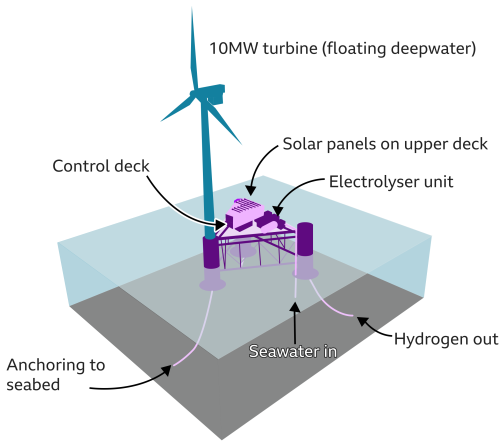


Figure 2.3: Plan for offshore production of hydrogen for the ERM dolphyn project[26].

The ZEEDS (Zero emission energy distribution at Sea) concept by ABB are similarly conceptualizing a floating hub for zero emission fuels, mainly Ammonia. Their calculations predict that each 12 MW FOWT supplies enough power to produce fuel for one ship per day. The fuel would then be stored in seabed tanks to keep the fuel liquid, reducing the power demand from the fuel storage units. To avoid port congestion and reduce operational downtime they plan to make use of autonomous vessels distributing the fuel by STS bunkering[27].

Enabling production far offshore gives the opportunity to place the energy replenishment stations in better position for the vessels. There are however several limitations when it comes to the placement of such structures, one of these is the water depth. To maintain a fixed position the structure will most likely need some form of mooring, currently most fields for floating offshore wind farm development are in the range of 80-200m depth. The deepest operating oil & gas installation is currently the Stones projects FPSO operating at about 2900m, while the Perdido platform is the worlds deepest spar moored at 2450m[28]. The average depth of the North Atlantic Ocean and the Pacific Ocean is about 3500 m and 4300m respectively, meaning that for large parts of the oceans a mooring option would be infeasible[29].

Direct charging in offshore wind turbine

Maersk Supply Service and Ørsted have joined forces in a project where they are looking into opportunities for vessels to directly exploit offshore energy being produced nearby[30]. In Figure 2.4 the schematics of the concept can be seen. Vessel A is receiving power directly from the turbine, while the two vessels B charge through a buoy. The concept is mainly targeted at idle vessels of Service Operation Vessel size, but efforts are made to scaling the buoy solution for larger vessels.

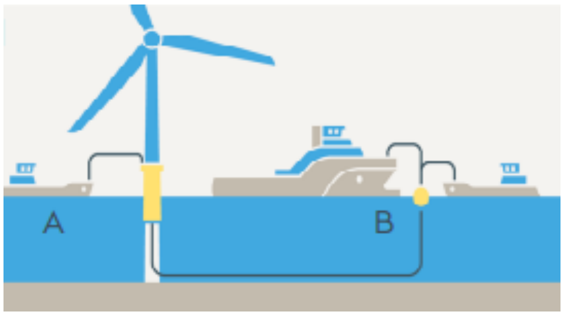


Figure 2.4: Illustration of vessels charging with Ørsted and Maersk concept[31]

Designated Recharging Vessel

The concept vessel THOR by Ulstein shown in Figure 2.5 is based on Nuclear technology with a Thorium molten salt reactor to generate electricity enough to recharge future battery driven expedition cruise ships operating in remote areas [32]. The vessel is designed as a multi purpose vessel able to perform research tasks as well as search and rescue operations. A vessel such as this could possibly enable many battery powered vessels to operate remotely.

Figure 2.5: Thor [32]

Chapter 3

Methodology

In this chapter the methods within operations research that is to be used for finding the optimal location for energy replenishment stations for zero-emission vessels will be presented and a literature review of work done on similar problem definitions.

3.1 Motivation for using operation research

In this thesis the goal is to develop a decision support tool for finding discrete optimal location for energy replenishment stations for zero-emission ships based on their port calls. To enable the switch from fossil fuels and facilitate for zero emission vessels significant infrastructural decisions need to made, involving large investments which in turn mean that a sub optimal or wrong decision will be costly. Modelling the decision as a mathematical optimization problem can supply the decision maker with a tool that outputs the optimal location based on the input parameter retrieved and can be a valuable result in the larger process of developing a scenery suitable for zero-emission vessels.

3.2 Operation research

In this section a general introduction to operation research is given. In an effort to improve decision making processes Operation Research (OR) has played an important role in modern history. The development of OR accelerated during world war II and continued the development for non-military applications in the following years and has played a significant part in solving a wide range of challenges. These challenges are often multifaceted and demanding to solve without computational assistance. As an example for a company, OR can aid with major business decisions such as which investments to make, how to best structure a service route, time scheduling of tasks and location of facilities[33]. The research part in operations research often involves using the scientific method when analyzing and modelling the operations under scrutiny. When the operation has been identified as a candidate for using OR-methods a more or less fixed set of steps is followed in the continued process seen in Figure 3.1.

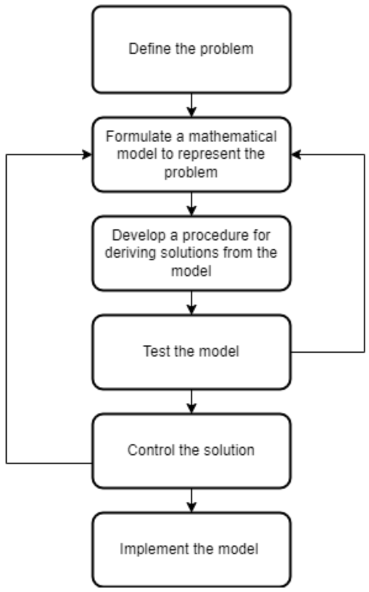


Figure 3.1: Phases within OR.

The first step in Figure 3.1 involves studying the problem at hand thoroughly to be able to define it precisely and collect relevant data for the model. Next a mathematical model is formulated abstracting the essence of the defined problem making it convenient for analysis. Further a procedure of deriving solutions from the model must be developed. This is typically a computer-based procedure as it is in this thesis. When an iteration of the model has been developed it should be tested to detect and correct bugs. Ensuring that the elements in the model have the desired interrelation and increasing the validity of the model. Before implementing the model the solution output is controlled to be within the desired degree of satisfaction. If the controlled variables are changed significantly this may trigger a need for change in the mathematical formulation in order to keep the model solution under control. Finally the fully developed model is to be implemented as a decision support tool as prescribed by the users.

3.3 Mathematical formulations

As presented the goal of developing a mathematical model is to give decision support for the location of offshore energy replenishment stations on the basis of vessel port calls. The problem of directing the traffic flow in an optimal direction with respect to cost can be looked upon as a network optimization problem. A special variant of network optimization problem is the facility location problem. A model type designed to find the optimal location of facilities with regard to some demand.

3.3.1 Network optimization

In modern day life, we are surrounded by concepts that can be described as networks: our transportation industry, the electrical grid and tools of communication are just some examples. The application of networks to solve and visualize problems is also prominent within production, supply chain management, financial planning, and facility location etc.[33]. By definition, a network consists of a set of nodes connected by a set of arcs. Arcs can be directed (only flow in one direction) or undirected (flow both ways). Dealing with a set of discrete locations spatially distributed and connected by the vessels predetermined routes the environment looks familiar to a network within operations research.
The minimum cost flow problem holds a central position among the network optimization methods. It can be solved very efficiently formulated as a linear programming problem. The fundamental building blocks of the formulation is applicable for a wide range of problems. The objective in minimum cost flow problems is to minimize the total cost of satisfying a demand with a supply through the network. The network is directed with at least one supply node and at least one demand node. With the remaining nodes being transshipment nodes. e.g. a ship is transporting a goods from a supply port through a set of nodes to the port of demand.

3.3.2 Optimal location

Optimal location problems are widely applicable. In most industries, the location of production facilities, storage facilities and distribution network are one of the most important and cost driving decisions. Location theory was formalized in 1909 with the problem of finding the optimal location of a single warehouse by minimizing the total travel distance between the warehouse and a set of spatially distributed customers[34]. Facility location problems (FLP) is a subcategory of network optimization problems handling the location of facilities with regard to demand centers in discrete locations in the case of this thesis, energy replenishment need from ships through establishment of energy replenishment stations.

3.4 Literature review

This chapter aims to give an input to some of the work that has been done related to optimal location of energy replenishment stations. There are currently very limited published material where the principles of mathematical optimization have been used to identify the optimal location for an energy replenishment stations for vessels running on zero-emission energy systems. There are however multiple studies assessing the techno-economic feasibility of such facilities in addition to extensive literature on optimal refueling strategy for a vessel point of view with conventional ICE's.

3.4.1 Optimal bunker fuel management

The oil price is fluctuating by nature and as a consequence so is the fuel price for the vessel operators. The fuel cost is generally a major cost component for maritime transport. The fuel price offered in different ports is often not the same and refueling in a high cost location when alternatives are available is not efficient. A study by Zhen *et al.* [35] investigates an optimal control policy for a ship in liner traffic to decide at which port and how much fuel the vessel should be refueled. They use a dynamic programming approach to give decision support. They included the fuel price in each port as a stochastic variable. Likewise they considered the fuel consumption between ports to also be stochastic due to the impact of weather/sea conditions, speed, draft, trim and the power consumed by all kinds of systems on the vessel. The results after several case examples concludes that with the model up to 8 % fuel consumption costs can be saved.

Similarly a paper by Yao *et al.* [36] develops a model for the bunker fuel management for a ship in liner service. In addition to refueling port selection and determination of how much to bunker to be supplied in each location, they also include the speed as a decision variable in the model, but the vessel must still be able to complete the schedule on time. Testing the model on two intercontinental routes the researchers found that the optimal port selection varied with time and that the common practice of today only having a few fixed ports for refueling could be improved. The main drivers for port selection was the price evolution of the fuel while for the speed determination of the vessel the time windows played the most important role. Other than changing the schedules and skipping some nonstrategic ports they also found that increasing the bunker fuel capacity of the vessels could give relatively significant fuel related cost savings.

In the paper by Wang and Chen [37] multi-port and multi-route container ship refueling and sailing speed optimization model is presented. The results of their model tested on a shipping route between Asia and Europe visiting 14 ports, gave interesting results with regards to influence of change in fuel price, container transport amounts, bunker capacity and carbon tax rate on the container ship deployment, ship size, refueling pattern and speed. Among their findings was that the fuel price initially only influenced voyage costs, but with further increase lead to a sharp increase in number of ships deployed and the total sailing time, while the refueling amounts and average speeds decreased. Increasing the amount of container to be transported the total shipping costs also increased and the refueling amounts increased sharply then kept constant. This was also the case for the average sailing speed. The number of ships deployed and the total sailing time reacted oppositely and decreased before keeping constant. Increasing the fuel capacity lead to a decrease in the total shipping costs, but for the other parameters the results were mixed. The number of ships reacted unstably with an initial increase then becoming more unpredictable, the refueling amounts increased initially before showing tendency to decrease and then kept unstable. The total sailing time and the average sailing speed where unstable at first and then remained constant with further increase in fuel capacity.

3.4.2 Optimal position for hydrogen refueling stations

In the paper by Mao *et al.* [38] they look into the feasibility of the vessels trafficking the US-China Pacific container corridor to be powered by hydrogen fuel cells. By obtaining vessels specific data and such as size, speed, travel pattern and fuel tank capacity and using empirical formulas they calculated the attainment rate for the vessels if they ran on hydrogen with the same fuel capacity. They found that 79% of the legs could be completed however almost all the voyages included one long leg so for the whole voyage the attainment rate for the vessels dropped to 43 %. Worth noticing, the researchers found that the attainment rate was largest for the medium sized container vessels. The smaller and larger ones had less space for larger fuel tanks without sacrificing cargo. Further they tested how they could elevate the attainment rate by adding port calls along the route for refueling and adding additional fuel capacity. They found that by adding just one stop or sacrificing 5% of the cargo space for fuel tank capacity nearly all of the voyages could be completed by using hydrogen as fuel. In the paper they only considered existing ports that had the possibility to facilitate the vessels. A follow up study was performed for the same case looking into the infrastructure needed for the refueling scenario to come alive Georgeff *et al.* [39]. They identified two options for refueling, having a stationary storage tank or having a designated refueling vessel. Using the traffic studied by Mao *et al.* [38] they calculated the required capacity of the different refueling locations. The interplay between flexible vessels and stable demand carrying tanks is illustrated in Figure 3.2.

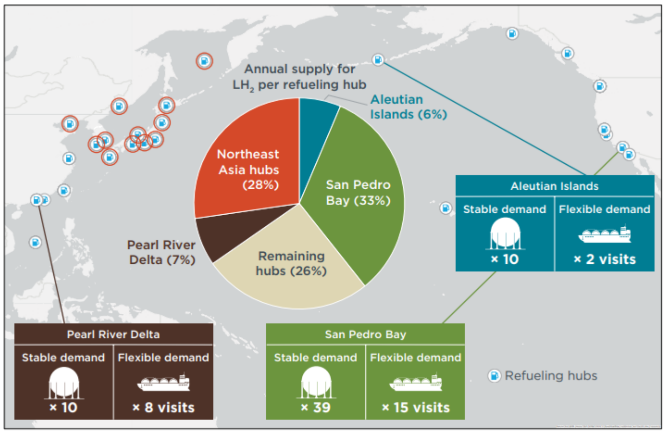


Figure 3.2: Hydrogen demand and the infrastructure needed to supply the US-China container traffic [39].

Chapter 4

Discrete optimization of energy replenishment location

In this chapter the development of an optimization model to solve the optimal location of energy replenishment stations for zero-emission vessels is presented step by step.

4.1 Overall problem description

To facilitate the transition toward zero-emission vessels new supporting solutions in the form of energy replenishment infrastructure needs to be put in place. On the basis of a vessel traffic pattern between ports locate the optimal position of the energy replenishment stations and the corresponding required energy storage capacity of the vessels. The energy storage capacity comes at the expense of lower cargo transport capacity. The vessels have a given energy consumption per distance unit covered and a corresponding voyage cost. The energy replenishment stations rely on a supply from an energy supply hub and in addition to a fixed cost of establishing a station there is a cost directly correlated with the distance from the energy supply hub.

4.2 Model for single energy replenishment location

Initially a simple version of the problem is to be solved. This section will present an optimization model for the optimal position of a energy replenishment station for a cargo vessel transporting goods from a port of origin to a port of destination as shown in Figure 4.1. The model presented in this section will form the basis for further model expansions. In essence this simplification of the main problem is a facility location problem where one facility is to be placed in order to serve the two ports nodes.

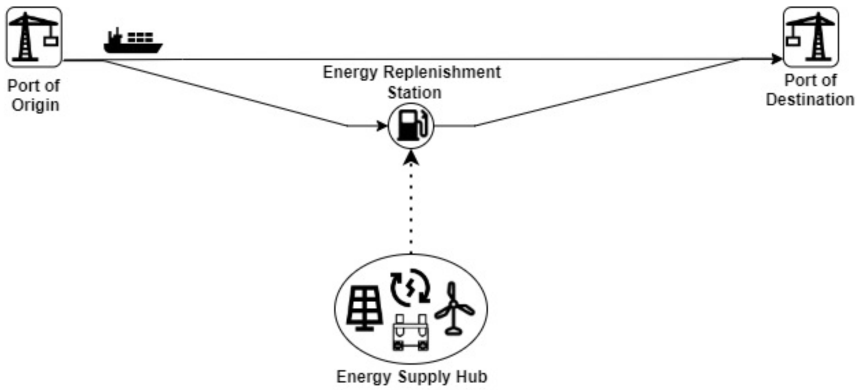


Figure 4.1: Problem illustration

Problem definition

A vessel is servicing a cargo route between two ports. The vessel has a flexible energy storage capacity (k) affecting the ability to transport cargo which introduces a lost opportunity cost (C^{LOC}) per unit of k. k is limited by the combined available space for both cargo and energy storage K. The vessel has an energy consumption F and voyage cost C^V per unit distance travelled. An energy replenishment station is to be established in one of the potential locations N^R to serve the vessel. An energy supply hub H services the energy replenishment station and the cost of supply C^H is proportionate to the distance S_{Hj} between the hub and the station.

4.2.1 Mathematical formulation

Definitions

In Figure 4.2 the sets, parameters and variables to be described in Table 4.1 are shown.

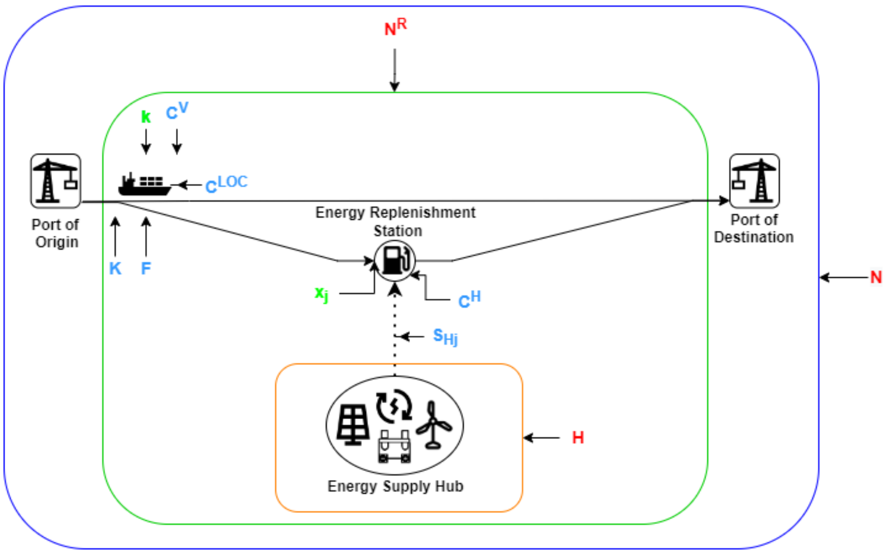


Figure 4.2: Overview of notation

Sets	
N	Set of nodes including O, the port of origin and D, the port of destination.
N^R	Set of possible energy replenishment locations including the hub (H), $N^R \subset N$.
Parameters	
C^V	The voyage cost per distance unit for the vessel.
C^{LOC}	Lost opportunity cost per unit of vessel energy storage capacity.
C^H	The additional cost per distance unit from the energy supply hub of operating a energy replenishment station.
K	Available space for cargo and energy storage in the vessel.
F	Energy consumption per distance unit with the vessel.
S_{ij}	Distance from node i to node j.
Variables	
k	Energy storage capacity of vessel.
x_j	1 if vessel visits an energy replenishment station in node j, 0 otherwise.

Table 4.1: Definitions

Objective function

The objective function is a minimum cost function. It consists of three cost components.

- The voyage cost between the ports and the energy replenishment station.
- The lost opportunity cost related to how much space the energy storage capacity occupies on the vessel.
- The cost of service of the energy replenishment station from the energy supply hub.

$$min \sum_{j \in N^R} \left(x_j (S_{Oj} + S_{jD}) C^V \right) + kC^{LOC} + \sum_{j \epsilon N^R/\{H\}} \left(x_j S_{Hj} C^H \right) \tag{4.1}$$

Constraints

Energy replenishment station. Constraint (4.2) states that one energy replenishment station is visited in one of the possible locations.

$$\sum_{j \in N^R} x_j = 1. \tag{4.2}$$

Energy storage capacity. Constraint (4.3) ensures that the vessel does not take on voyages that demand more energy than the energy capacity of the vessel.

$$FS_{ij} x_j \leq k, \quad i \in N/\{N^R\}, j \in N^R. \tag{4.3}$$

Constraint (4.4) states that the energy storage capacity is non-negative and bound by the maximum available space for both energy storage and cargo.

$$0 \leq k \leq K. \tag{4.4}$$

Binary constraint. x_j is 1 if the vessel visits an energy replenishment station in node j and 0 otherwise.

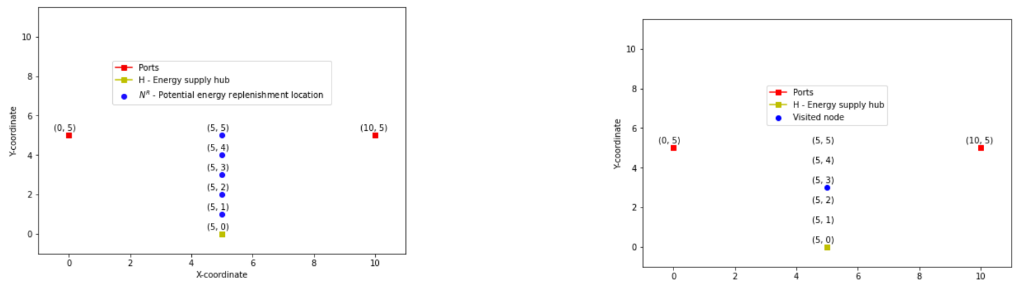
$$x_j \in \{0, 1\}, \quad j \in N^R. \tag{4.5}$$

4.2.2 Illustrative case

To illustrate the functionality of the model an example case is here solved by the model. The parameter values in are given in Table 4.2 and the coordinates for the nodes are shown in Figure 4.3a.

Parameter	Value
C^V	1
C^{LOC}	1
C^H	1
F	1
K	10

Table 4.2: Input values for the model



(a) Input coordinates to model

(b) Solution with selected node

Figure 4.3: Plots of the example case

Results & model evaluation

As can be seen in Figure 4.3b x_j equals 1 for node j with the coordinates $(5, 3)$ and the required energy storage capacity is $k = 5.86$ for the vessel. The model handles the trade-off between vessel related costs and energy replenishment station costs to find the optimal location. Increased cost of energy supply hub service cost moves the optimal position of the energy replenishment station closer to the hub, while the voyage cost combined with the lost opportunity cost pulls in the opposite direction. Without the energy supply hub the optimal location would obviously be in the center between the two ports to minimize the lost opportunity cost for the vessel.

4.3 Model for energy replenishment network for single vessel

This section presents an expanded model of the one introduced in section 4.2. The vessel is now allowed to visit an arbitrary number of energy replenishment stations between the ports. The structure of the problem can now be seen as a network of nodes and arches. The decision variable x_j from section 4.2 has now become a routing variable x_{ij}, determining which arches are to be used in the network as shown in Figure 4.4. The problem is no longer fixed to the location of one energy replenishment station and each station has a fixed cost C^S related to the establishment. From a structural view the modelling problem has changed to a combination of a facility location problem and network optimization problem where if an energy replenishment station node has a connecting arch then establishment cost follows for the same node.

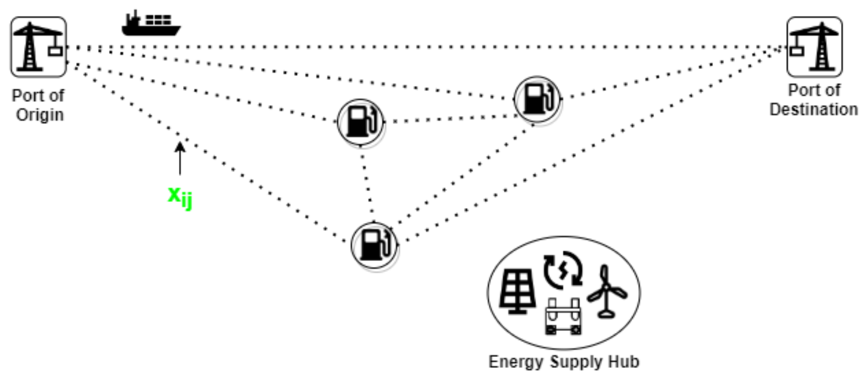


Figure 4.4: Problem illustration

4.3.1 Mathematical formulation

The structure of the model is now altered to handle the routing of the vessel through the network of nodes.

Definitions

A new set A is introduced which is the set of arcs connecting all of the nodes and the decision variable x_{ij} decides which arcs are to be utilized with the vessel. In addition C^S, the fixed cost of establishing a energy replenishment station is new. f_{ij} is a dependent variable which contains the energy consumed by the vessel between node i and j.

Sets	
N	Set of nodes including O, the port of origin and D, the port of destination.
N^R	Set of possible energy replenishment locations including the hub (H), $N^R \subset N$.
A	Set of arcs between all nodes in N.
Parameters	
C^V	The voyage cost per distance unit for the vessel.
C^{LOC}	Lost opportunity cost per unit of vessel energy capacity.
C^H	The additional cost per distance unit from the energy-supply hub of operating a energy replenishment station.
C^S	The fixed cost of establishing an energy replenishment station.
K^V	Available space for cargo and energy storage in the vessel.
F	Energy consumption per distance unit with the vessel.
S_{ij}	Distance from node i to node j.
Variables	
k	Energy storage capacity of vessel.
f_{ij}	The energy consumption from node i to node j.
x_{ij}	1 if vessel travels from node i to j, 0 otherwise.

Table 4.3: Definitions

Objective Function

The objective function minimizes cost with regards to:

- Voyage cost.
- Lost opportunity cost related to the energy storage capacity.
- Energy replenishment station fixed and location specific cost.

$$min \sum_{i,j \in A} x_{ij} S_{ij} C^V + kC^{LOC} + \sum_{i \in N} \sum_{j \in N^R/\{H\}} x_{ij} \left(C^S + S_{Hj} C^H \right) \tag{4.6}$$

Constraints

Energy storage capacity.
In constraint(4.7) f_{ij} is defined to be the energy consumed by the vessel between node i and j.

$$x_{ij} S_{ij} F = f_{ij} \quad i,j \in A \tag{4.7}$$

Constraint(4.8) ensures that the energy consumption between two nodes does not exceed the energy storage capacity.

$$0 \leq f_{ij} \leq k \quad i,j \in A \tag{4.8}$$

Constraint (4.9) states that the energy storage capacity is non-negative and bound by the maximum available space for both energy storage and cargo.

$$0 \leq k \leq K^V \tag{4.9}$$

Network flow.
There must be exactly one arc connected to node O, the port of origin.

$$\sum_{j \in N} x_{Oj} - \sum_{j \in N} x_{jO} = 1 \tag{4.10}$$

There must be exactly one arc connected to node D, the destination port.

$$\sum_{i \in N} x_{iD} - \sum_{i \in N} x_{Di} = 1 \tag{4.11}$$

Continuity in the power replenishment nodes where constraint(4.12) ensures that if the vessel has a connecting arch in to a node, then it must also have an arch going out.

$$\sum_{j \in N^R} x_{ij} - \sum_{j \in N^R} x_{ji} = 0 \quad i \in N, \tag{4.12}$$

Constraint(4.13) limits the number of arch's directly connecting two nodes to just one arch.

$$x_{ij} + x_{ji} \leq 1, \quad i,j \in A. \tag{4.13}$$

Variable definitions
Binary constraint

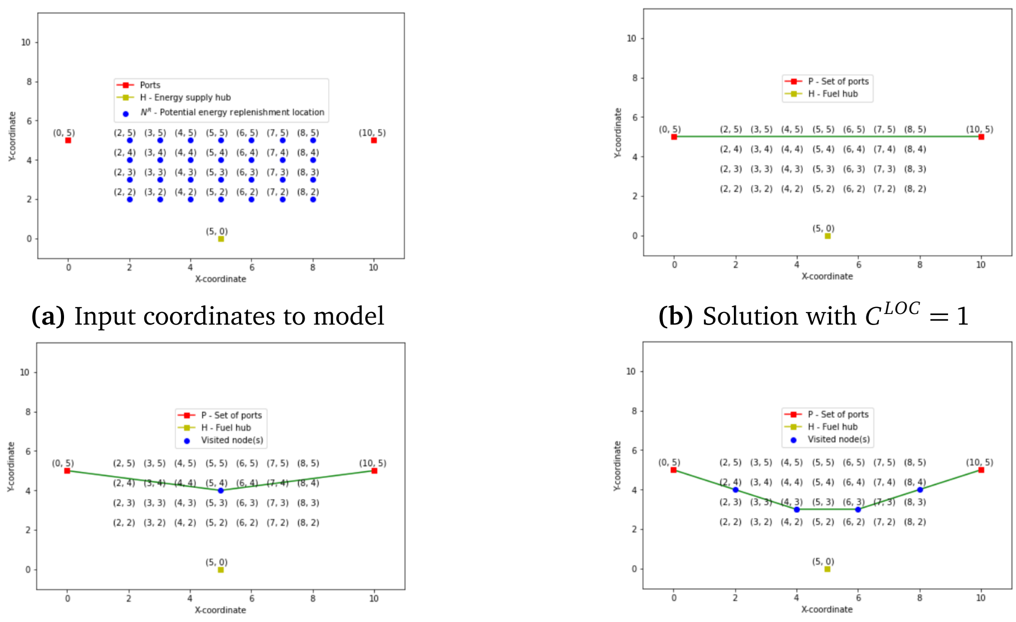
$$x_{ij} \in \{0,1\}, \quad i,j \in A. \tag{4.14}$$

4.3.2 Illustrative case

For the expanded model in this section a new example is generated. In Table 4.4 the input values for the model are listed. In the example three different values for C^{LOC} are given. The coordinates for the nodes are shown Figure 4.5a.

Parameter	Value
C^V	1
C^{LOC}	1/4/8
C^H	1
C^S	1
F	1
K^V	10

Table 4.4: Input values for the model



(a) Input coordinates to model

(b) Solution with $C^{LOC} = 1$

(c) Solution with $C^{LOC} = 4$

(d) Solution with $C^{LOC} = 8$

Figure 4.5: Plots of the case

Results & model evaluation

In Figure 4.5b the parameter values implemented in the model are listed. The values are identical to the previous model example except for the introduction of the new variable C^S. However for this case the optimal solution to the model is to go directly to the next port without energy replenishment with the energy storage capacity demand $k = 10$. For $C^{LOC} = 4$ Figure 4.5c shows the selected arches and position of the energy replenishment station in node (5,4). Increasing the lost opportunity cost to $C^{LOC} = 8$ the model selects four energy replenishment stations.

While having obvious similarities with the structure of a shortest path problem the model will prefer solutions with the shortest arches due to the C^{LOC} evoked by increase in vessel required energy storage capacity k.

4.4 Model for energy replenishment network for multiple vessels and energy supply hubs

A natural expansion for the model in section 4.3 is the inclusion of multiple vessels. Expanding the model to include multiple vessels means that individual characteristics must be handled correctly and a separate variable u_j for the establishment of energy replenishment locations is also introduced. Multiple energy supply hubs with their own area of responsibility as displayed in Figure 4.6 increases the size of the model environment.

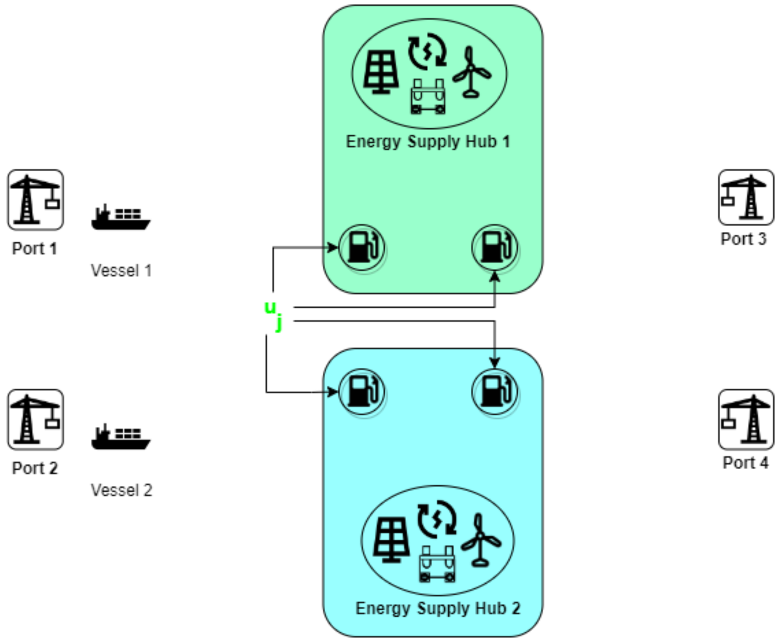


Figure 4.6: Model illustration

4.4.1 Mathematical formulation

Definitions

The vessel specific sets, parameters and variables have been updated with an index v. H_j is denoting the energy supply hub serving node j and allows for multiple energy supply hubs serving their own area of demand. The decision variable u_j is implemented to handle the establishment of energy replenishment stations with each vessel having their individual routing variable x_{ijv}.

Sets	
N	Set of nodes including O_v, the port of origin of vessel v and D_v, the port of destination for vessel v.
N^R	Set of possible energy replenishment locations including the hub H_j for each location, $N^R \subset N$.
A	Set of arcs between all nodes in N.
Parameters	
C_v^V	The voyage cost per distance unit for the vessel v.
C_v^{LOC}	Lost opportunity cost per unit of vessel v energy capacity.
C^H	The additional cost per distance unit from the energy-supply hub of operating an energy replenishment station.
C^S	The fixed cost of establishing an energy replenishment station.
K_v^V	Available space for cargo and energy storage in vessel v.
F_v	energy consumption per distance unit with vessel v.
S_{ij}	Distance from node i to node j.
Variables	
k_v	Energy storage capacity of vessel v.
f_{ijv}	Energy consumption from node i to node j with vessel v.
u_j	1 if an energy replenishment station is opened in position j, 0 otherwise.
x_{ijv}	1 if vessel v travels from node i to j, 0 otherwise.

Table 4.5: Definitions

Objective function

The essence of the objective function remains the same as in section 4.3, minimizing cost with regards to:

- Voyage cost.
- Lost opportunity cost related to the energy storage capacity.
- Energy replenishment station fixed and location specific cost.

$$min \sum_{v \in V} \sum_{j \in A} x_{ijv} S_{ij} C_v^V + \sum_{v \in V} k_v C_v^{LOC} + \sum_{j \in N^R / \{H_j\}} u_j \left(C^S + S_{H_j,j} C^H \right) \tag{4.15}$$

Constraints

Energy storage capacity.
In constraint(4.16)f_{ijv} is defined to be the energy consumed by vessel v between node i and j.

$$x_{ijv} S_{ij} F = f_{ijv} \quad i, j \in A, v \in V \tag{4.16}$$

Constraint(4.17) ensures that the energy consumption between two nodes does not exceed the energy storage capacity of vessel v.

$$f_{ijv} \leq k_v \quad i,j \in A, v \in V. \tag{4.17}$$

Constraint (4.18) states that the energy storage capacity of vessel v is non-negative and bound by the maximum available space for both energy storage and cargo on the specific vessel.

$$0 \leq k_v \leq K_v^V \quad v \in V \tag{4.18}$$

Network flow.
There must be exactly one arc going out from node O_v for vessel v.

$$\sum_{j \in N} x_{O_v jv} - \sum_{j \in N} x_{jO_v v} = 1 \quad v \in V \tag{4.19}$$

There must be exactly one arc going into node D_v for vessel v.

$$\sum_{i \in N} x_{iD_v v} - \sum_{i \in N} x_{D_v iv} = 1 \quad v \in V \tag{4.20}$$

Continuity in the power replenishment nodes where constraint(4.21) ensures that if vessel v has a connecting arch in to a node, then it must also have an arch going out.

$$\sum_{j \in N^R} x_{ijv} - \sum_{j \in N^R} x_{jiv} = 0 \quad i \in N, v \in V. \tag{4.21}$$

In constraint(4.22) states that there can be maximum one connecting arch between two nodes for each vessel.

$$x_{ijv} + x_{jiv} \leq 1, \quad i,j \in A, v \in V. \tag{4.22}$$

Energy replenishment station
An energy replenishment station must be established in node j if any of the vessels visits the node.

$$x_{ijv} \leq u_j, \quad i \in N, j \in N^R, v \in V. \tag{4.23}$$

Variable definitions
Binary constraint.

$$u_j \in \{0,1\}, \quad j \in N^R. \tag{4.24}$$

Binary constraint.

$$x_{ijv} \in \{0,1\}, \quad i,j \in A, v \in V. \tag{4.25}$$

4.4.2 Illustrative case

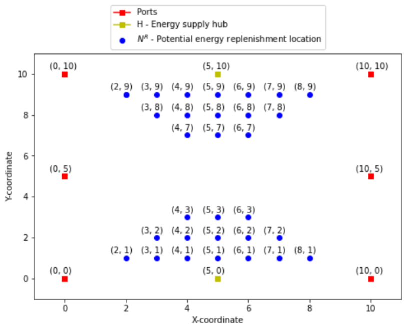
This example takes in three identical vessels with parameter values listed in Table 4.6, however the vessels are to serve individual routes between O_v and D_v listed in Table 4.7. The node environment they operate in is shown in Figure 4.7a.

Parameter	value
C_v^V	1
C_v^{LOC}	1
C^H	1/2/3
C^S	1
F_v	1
K_v^V	15

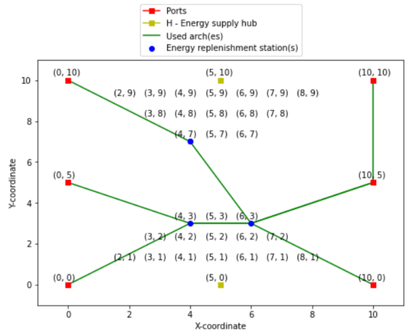
Table 4.6: Input values for the model

Node	$v = 1$	$v = 2$	$v = 3$
O_v	(0,0)	(0,5)	(0,10)
D_v	(10,10)	(10,5)	(10,0)

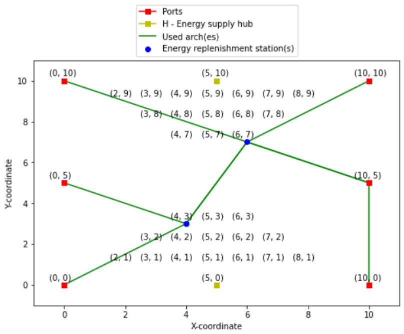
Table 4.7: Ports of origin and destination for the different vessels.



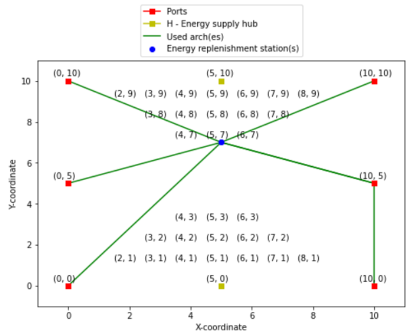
(a) Input coordinates to model



(b) Solution with $C^H = 1$



(c) Solution with $C^H = 2$



(d) Solution with $C^H = 3$

Figure 4.7: Plots of the case

Results & model evaluation

The plots in Figure 4.7b, Figure 4.7c and Figure 4.7d show the resulting energy replenishment node selection along with the selected arches by the vessels. With increasing cost of servicing energy replenishment stations from energy supply hub C^H it will become less lucrative to establish new stations far way from the supply hub node leading to longer arches being used by the vessel requiring more energy storage capacity as can been seen in Table 4.8.

Energy storage demand k_v	$C^H = 1$	$C^H = 2$	$C^H = 3$
k_1	5.0	5.0	8.7
k_2	4.5	4.5	5.4
k_3	5.0	6.8	5.9

Table 4.8: Required energy storage capacity in the different scenarios

Chapter 5

Optimal energy replenishment location for transatlantic container ship routes

In this chapter the deep sea container traffic connecting Europe and North America will be subject to research for liquid hydrogen powered vessels. The optimization model insection 4.4 will be further expanded to become applicable for the case.

5.1 Transatlantic container transport using liquid hydrogen as energy carrier

The transatlantic route between Europe and North America is one of the main container routes of the world with an annual container transport of 8 million teu[40]. Some of the busiest container ports in the Atlantic Ocean is located on the west coast of Europe and the north-east coast of America. In Figure 5.1 the world container volumes flow are shown, with the transatlantic route as one of the most prominent.

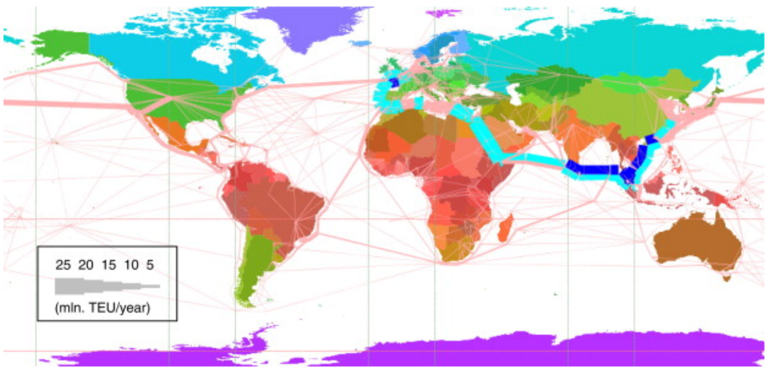


Figure 5.1: World container traffic flow[41]

5.1.1 Ports and energy hubs

There are multiple ports in both western Europe and North America serving as container shipment ports between the continents. Six of them will be used to find the optimal location of energy replenishment stations in between. In Table 5.1 the ports with their respective coordinates are listed. To serve the energy replenishment vessels three Atlantic islands have been chosen as potential energy replenishment hubs. They are listed along with their respective coordinates in Table 5.2. Energy replenishment vessels can operate from these hubs in a set of discrete locations. The specific locations can be found in Figure A.2. In Figure 5.2 the location of both the ports and potential energy hubs are shown.

Port	Coordinates (LAT/LON)
Rotterdam (NL)	51.8850/4.2867
Lisbon (PT)	38.6994/-9.1714
Algeciras (ES)	36.1402/ -5.4366
Newark(US)	40.6675/-74.1452
Savannah (US)	32.1235/ -81.1358
Halifax (CA)	44.6334/ -63.5625

Table 5.1: Port coordinates

Port	Coordinates (LAT/LON)
Island	63.8370/-22.4327
Azores [PT]	39.4519/-31.1254
Bermuda [GB]	32.3148/-64.7190

Table 5.2: Hydrogen supply hub coordinates

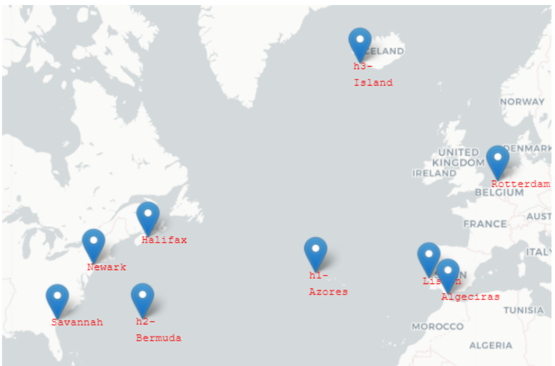


Figure 5.2: Ports and potential energy hubs

5.1.2 Container Vessels & energy consumption

The container vessels in international traffic varies in size and capacity. In Table 5.3 a statistical mean fuel consumption for container vessels running on fuel oil have been converted to liquid hydrogen consumption. Assuming a relative superior system efficiency of 1.2 and adjusting for relative energy density in the fuels. In

	Liquid hydrogen consumption [tons/day]		
Size [Teu]	18 kn	20 kn	24 kn
4000-5000	16	23	44
5000-6000	17	27	50
7000-8000	23	34	66
8000-9000	31	44	81
10000+	42	55	103

Table 5.3: Liquid hydrogen consumption [42].

Table 5.4 hydrogen consumption in m^3 per nm for the same vessels is listed.

	Liquid hydrogen consumption [m^3/nm]		
Size [Teu]	18 kn	20 kn	24 kn
4000-5000	9.2	13.8	25.7
5000-6000	10.1	15.6	29.3
7000-8000	13.8	20.2	38.5
9000-10000	18.3	25.7	47.7
10000+	24.8	32.1	60.5

Table 5.4: Liquid hydrogen consumption.

5.1.3 Container vessel charter rates

In Table 5.5 available daily charter rates for container vessels of various sizes are listed . The charter hire pays for all operational costs for the vessels except for fuel cost, port fees and other voyage dependent expenses before profit.

Vessel size [Teu]	charter rate[day]
8000	65 000$
6500	55 000$
4250	50 000$
3500	48 000$
1700	40 000$

Table 5.5: Container vessel charter rates [43].

5.1.4 Container Freight

The Freightos baltic index (FBX) measure the daily 40-foot container freight rate. FBX22 is the index measuring rates from northern Europe and northern America, while FBX 21 handles the return rates. Container freight rates can be volatile and are easily affected by changes in the global supply chains. FBX22 is dominating FBX21 due to the relatively higher demand for container transport from West Europe to North America than the other way around. The volume of each 40-foot container is 67.7 m^3.

Index	Freight rates
FBX21	8381$
FBX22	618$

Table 5.6: Container freight rates for 40-foot container (20.05.2022) [44].

5.1.5 Hydrogen storage system

A fuel cell is relatively more handy on a vessel compared to a conventional engine as it is more flexible in where it can be located on the vessel. The liquid hydrogen storage system on the other hand demands more advanced components, more space and it is generally much more complex in order to keep to hydrogen at low enough temperatures to keep it liquid. For insulation and other support mechanisms the storage space needed is about 20% in addition to the volume occupied by the hydrogen. As with lng storage tanks, the liquid hydrogen tanks cannot be completely depleted before replenishment as they would need to be cooled down again. A process that is time consuming and leaves the vessel unable to operate. Between 10-30% of the liquid hydrogen storage capacity needs to be there at all times to keep the required storage conditions.

5.1.6 Energy price

The market for oil-based fuel products is relatively well functioning and you can expect the prices to be similar globally and cheapest in the large refueling hubs. This is due to the ease in which oil products can be transported from supply to demand locations. For the case of hydrogen like the natural gas marked, it is more exposed to regional price differences. They cannot be transported as cheap and easy. In a zero-emission scenario many vessels will rely on energy carriers produced with renewable electricity. The future green hydrogen price will be dependent on the availability of cheap clean electricity. In Table 5.7 the projected price of green hydrogen in the ports and energy supply hubs is listed.

Location	Green hydrogen cost per kg
Portugal	5.2$
Spain	5.2$
Netherlands	4.1$
Canada	4.1$
USA	4.7$
Iceland	2.8$
Azores [PT]	-$*
Bermuda [GB]	-$*

Table 5.7: Projected green hydrogen cost for different locations[45]. *no available data.

5.1.7 Energy replenishment station and hub

As energy supply hubs the Azores, Iceland and Bermuda have been chosen in this thesis. Liquid hydrogen bunkering vessels will function as energy replenishment stations and use the hubs as supply base. The possible locations for the energy replenishment stations are close to the energy supply hubs they are served by and a full overview of locations can be seen in the appendix, Figure A.2 and Table A.1.

5.2 Mathematical formulation

In this section the problem of selecting optimal location for hydrogen replenishment stations for maritime container traffic and corresponding required hydrogen storage capacity for the different routes between western-Europe and North-America will be formalized as an expansion of the mathematical model presented in section 4.4. Energy replenishment vessels can be deployed to serve the container shipping corridors between western Europe and North-America. They can perform energy replenishment operations in a set of discrete locations in connection to energy supply hubs at the Azores, Iceland and Bermuda respectively.

5.2.1 New notation

To further expand the model new variables to handle the amount of energy replenished in each location by each vessel is introduced. This will allows for further implementation of location dependent energy costs and energy replenishment decisions. In Figure 5.3 the new variables are shown and further explanation of new notation is found in Table 5.8. A full list of notation in this model can be found section A.2.

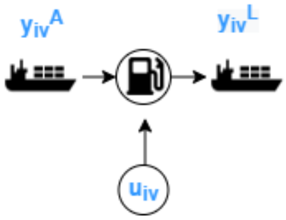


Figure 5.3: Illustration of the variables in the expanded model.

	Parameters
C_i^E	Energy cost in location i.
K_i^S	The maximum energy delivery capacity of energy replenishment station i.
P^M	Factor accounting for portion of energy left as margin.
P^I	Factor accounting for additional portion of space needed for insulation and other systems to serve the energy storage system.
	Variables
q_{iv}	Energy units replenished for vessel v in node i.
y_{iv}^A	Ship energy inventory when arriving at port i.
y_{iv}^L	Ship energy inventory when leaving port i.

Table 5.8: Definitions of new notation.

5.2.2 Model

The new model has been expanded to include the new parameters. In addition to the objective function constraint (5.3) has been altered, while (5.9)-(5.13) and (5.15)-(5.18) are new constraints.

Objective function.

The objective function has been altered to include P^I, the insulation factor for the hydrogen storage tanks in the calculation of the lost opportunity cost, and a new term for the cost of total amount of hydrogen replenished.

$$min \sum_{v \in V} \sum_{j \in A} x_{ijv} S_{ij} C_v^V + \sum_{v \in V} k_v P^I C_v^{LOC} + \sum_{j \epsilon N^R / \{H_j\}} u_j \left(C^S + S_{H_j,j} C^H \right) + \sum_{v \in V} \sum_{i \in N} q_{iv} C_i^E \tag{5.1}$$

Constraints

$$x_{ijv} S_{ij} F = f_{ijv} \quad i,j \in A, v \in V \tag{5.2}$$

$$f_{ijv} P^M \leq k_v \quad i,j \in A, v \in V. \tag{5.3}$$

$$\sum_{j \in N} x_{O_v jv} - \sum_{j \in N} x_{jO_v v} = 1 \quad v \in V \tag{5.4}$$

$$\sum_{i \in N} x_{iD_v v} - \sum_{i \in N} x_{D_v iv} = 1 \quad v \in V \tag{5.5}$$

$$\sum_{j \in N^R} x_{ijv} - \sum_{j \in N^R} x_{jiv} = 0 \quad i \in N, v \in V. \tag{5.6}$$

$$x_{ijv} + x_{jiv} \leq 1, \quad i,j \in A, v \in V. \tag{5.7}$$

$$x_{ijv} \leq u_j, \quad i \in N, j \in N^R, v \in V. \tag{5.8}$$

$$y_{O_v v}^L = k_v \quad v \in V. \tag{5.9}$$

$$y_{D_v v}^A = k_v \quad v \in V. \tag{5.10}$$

$$y_{jv}^A = y_{iv}^L - f_{ijv} \quad i \in N, j \in N / \{O_v\}, v \in V. \tag{5.11}$$

$$q_{iv} = y_{iv}^L - y_{iv}^A \quad i \in N / \{O_v\}, v \in V. \tag{5.12}$$

$$\sum_{v \in V} q_{iv} \leq K_i^S, \quad i \in N^R \tag{5.13}$$

$$0 \leq k_v \leq K_v^V \quad v \in V \tag{5.14}$$

$$0 \leq y_{iv}^A \leq k_v, \quad i \in N, v \in V \tag{5.15}$$

$$0 \leq y_{iv}^{L} \leq k_v, \quad i \in N, v \in V \tag{5.16}$$

$$q_{iv} \geq 0, \quad i \in N, v \in V \tag{5.17}$$

$$u_j \in \{0,1\}, \quad j \in N^R. \tag{5.18}$$

$$x_{ijv} \in \{0,1\}, \quad i,j \in A, v \in V. \tag{5.19}$$

In constraint (5.2) f_{ijv} is defined to be the hydrogen consumed by vessel v between node i and j. Constraint (5.3) ensures that the hydrogen consumption between two locations does not exceed the hydrogen storage capacity of vessel v. Constraint (5.4) states that there must be exactly one arc going out from node O_v for vessel v while constraint (5.5) states there must be exactly one arc going into node D_v for vessel v. In constraint (5.6) continuity in the hydrogen replenishment station nodes is ensured. Constraint (5.7) states that there can be maximum one connecting arch between two nodes for each vessel. Constraint (5.8) makes sure a hydrogen replenishment station is established in node j if any of the vessels visits the node. Constraint (5.9 states that departing from the port of origin the energy storage inventory is full and constraint (5.10) states that the energy storage inventory must be replenished after the route is serviced. Constraint (5.11) ensures that when a vessel arrives at the next port the energy inventory is equal to the amount the vessel had leaving the previous location minus the energy consumption between the locations. Constraint (5.12) sets the amount of energy replenished at location i equal to the amount the vessel had leaving location i minus the amount it had when it arrived. Constraint (5.13) ensures the energy replenished in energy replenishment station i does not exceed the maximum capacity of the station. Constraint (5.14) states that the energy storage capacity of vessel v is non-negative and bound by the maximum available space for both energy storage and cargo on the specific vessel. Constraint (5.15) and (5.16) ensures the energy storage inventory when arriving/leaving location i is not higher than the maximum energy storage capacity of the vessel and non-negative. Constraint (5.17) ensures the replenishment is non-negative. Constraint (5.18) and (5.19) are binary constraints.

5.3 Results

In this section the results from the optimization model are presented. First the model is solved for the original values in Table 5.9. Then the model parameters are altered to see what implications this has on the the variables and choice of optimal location for replenishment. The ports of origin and destination for the different routes travelled by the vessels are shown in Table 5.11. The parameters are based on data for 8000 Teu container vessels and the information provided in the previous section.

Parameter	Value
C^{LOC}	118 $\$/m^3$
C^S	50000 $
C^H	125 $\$/nm$
C^V	44 $\$/nm$
F	7.4 m^3/nm
K^S	500000m^3
K^V_v	550000m^3
C^E_{Hub}	200 $\$/m^3$
C^E_{port}	355 $\$/m^3$
P^M	1.36
P^I	1.2

Table 5.9: Case parameters

5.3.1 Base case

Figure 5.4 shows the resulting route selection of connecting each European port to each of the North-American ports. In addition to the ports an energy replenishment station is established in location (41,-34) using the Azores as an energy replenishment hub. In Table 5.10 the portion of liquid hydrogen replenished by location is listed. In Table 5.11 the different routes travelled by the vessels, required hydrogen storage capacity and total hydrogen replenished by each vessel travelling its respective routes are listed.

Node	Energy replenishment share
Newark	11%
Savannah	6%
Halifax	43%
Azores (41,-32)	40%

Table 5.10: Energy replenished by location

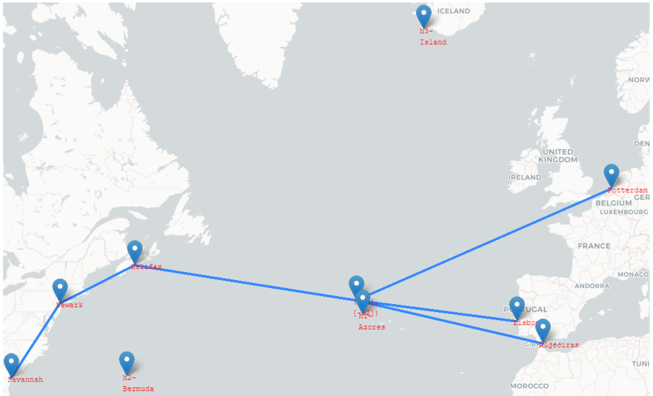


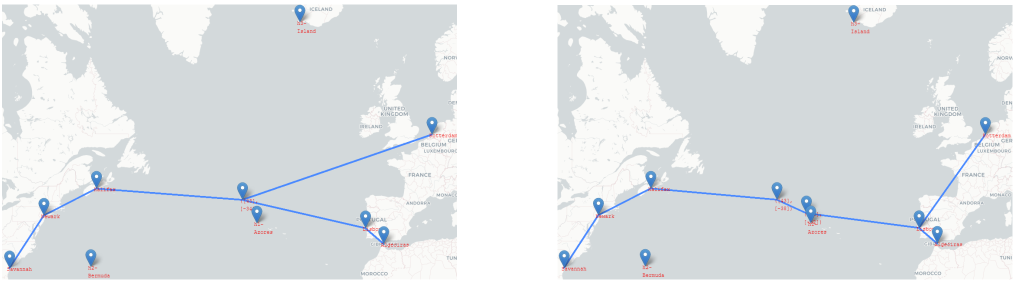
Figure 5.4: Resulting routes and energy replenishment locations

Vessel	O_v	D_v	$k_v\ [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$
1	Rotterdam	Newark	31 888	48 482
2	Rotterdam	Savannah	31 888	56 892
3	Rotterdam	Halifax	31 888	41 302
4	Lisbon	Newark	27 587	40 878
5	Lisbon	Savannah	27 587	49 248
6	Lisbon	Halifax	27 587	33 658
7	Algeciras	Newark	27 587	43 811
8	Algeciras	Savannah	27 587	52 222
9	Algeciras	Halifax	27 587	36 633

Table 5.11: Resulting energy storage capacity and total energy consumption for the vessels

5.3.2 For different vessel speeds

Applying the same values as in subsection 5.3.1, but changing the vessel speed to 20 kn and 24 kn gives the solution shown in Figure 5.5. Increasing the speed from 18kn to 20kn an additional energy replenishment stop in Lisbon is introduced and the optimal location for energy replenishment station is moved to (43,-34) still supplied by the Azores. For vessel speed of 24kn new energy replenishment stations in location (41,-32) and (43,-38) become part of the optimal solution. In Table 5.12 the share of hydrogen replenished in different locations is listed. The pattern of replenishment changes with speed. In Table 5.13 the difference in required hydrogen storage capacity and total hydrogen amount replenished compared to the base case in subsection 5.3.1 for the different vessels is listed.



(a) $V = 20kn$ **(b)** $V = 24kn$

Figure 5.5: Connected nodes and selected energy replenishment station location for different vessel speed

Node	V=20kn	V=24kn
Lisbon	2%	12%
Newark	11%	10%
Savannah	6%	6%
Halifax	40%	32%
Azores (41,-32)		31%
Azores (43,-34)	41%	
Azores (43,-38)		9%

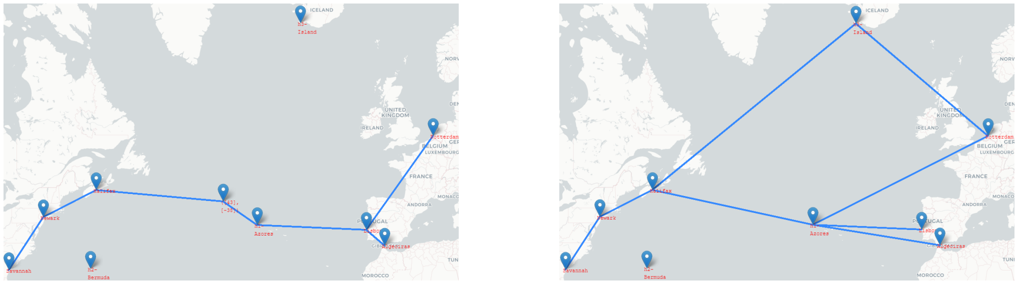
Table 5.12: Energy replenished by location

Vessel	$V = 20kn$		$V = 24kn$	
	$k_v\ [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$	$k_v [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$
1	+48%	+43%	+93%	+214%
2	+48%	+43%	+93%	+209%
3	+48%	+42%	+93%	+220%
4	+35%	+46%	+123%	+181%
5	+35%	+46%	+123%	+181%
6	+35%	+46%	+123%	+181%
7	+35%	+47%	+123%	+183%
8	+35%	+47%	+123%	+183%
9	+35%	+47%	+123%	+183%

Table 5.13: Resulting energy storage capacity and total energy consumption for vessels at 20 kn and 24 kn

5.3.3 For different lost opportunity costs

In Figure 5.6 the result of doubling the lost opportunity cost and cutting it by 50 % can be seen. In the first case the refueling hub at the Azores is visited directly and another station in location (43,-38) is established with supply from the Azores. Cutting the lost opportunity cost by 50% the hub at the Azores is still visited, but a new station is established on the energy replenishment hub on Iceland. In Table 5.14 the portion of liquid hydrogen replenished in the different locations is listed. In Table 5.15 the resulting energy storage capacity and total energy consumed by the vessels is listed.



(a) $2 \cdot C^{LOC}$ **(b)** $C^{LOC}/2$

Figure 5.6: Connected nodes and selected energy replenishment station location for different lost opportunity cost

Node	$2 \cdot C^{LOC}$	$C^{LOC}/2$
Lisbon	12%	
Newark	10%	11%
Savannah	6%	6%
Halifax	32%	47%
Iceland		7%
Azores	29%	29%
Azores (43,-38)	11%	

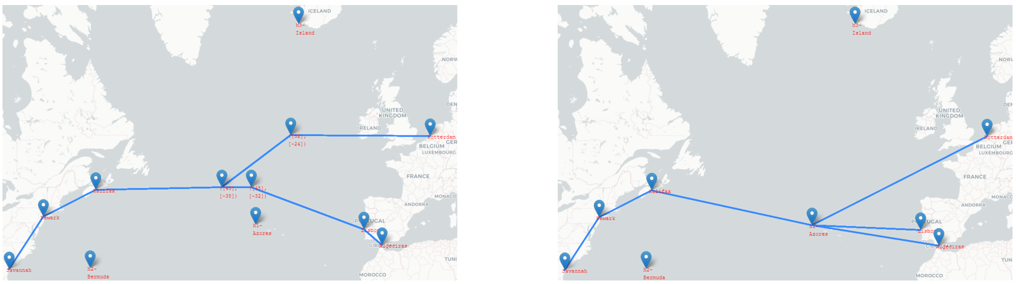
Table 5.14: Energy replenished by location

Vessel	$2 \cdot C^{LOC}$		$C^{LOC}/2$	
	$k_v\ [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$	$k_v [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$
1	-31%	+13%	+11%	-3%
2	-31%	+11%	+11%	-3%
3	-31%	+15%	+2%	3%
4	-21%	+2%	+5%	+1%
5	-21%	+1%	+5%	+1%
6	-21%	+2%	+5%	+1%
7	-21%	+2%	+5%	+1%
8	-21%	+2%	+5%	+1%
9	-21%	+3%	+5%	+1%

Table 5.15: Resulting energy storage capacity and total energy consumption for vessels with different lost opportunity cost.

5.3.4 For different cost of supply from energy supply hub

The result of reducing the cost of supply from hub to 0 can be seen in Figure 5.7a where three energy replenishment stations are part of the solution. Two of them in connection to the Azores in location (45,-32) and (45,-32). The last one is supplied by the hub on Iceland in location (52,-24). Changing the cost of supply from hubs to two times the original cost as in Figure 5.7b the only station established is on the Azores supply hub. In Table 5.16 the share of liquid hydrogen replenished in the different locations is listed. In Table 5.17 the difference in required hydrogen storage capacity and total hydrogen amount replenished compared to the base case in subsection 5.3.1 for the different vessels is listed.



(a) $C^H = 0$ **(b)** $2 \cdot C^H$

Figure 5.7: Connected nodes and selected energy replenishment station location for different lost opportunity cost

Node	$C^H = 0$	$2 \cdot C^H$
Lisbon	2%	
Newark	11%	11%
Savannah	6%	6%
Halifax	34%	44%
Iceland(52,-24)	11%	
Azores		39%
Azores (45,-38)	13%	
Azores (45,-32)	23%	

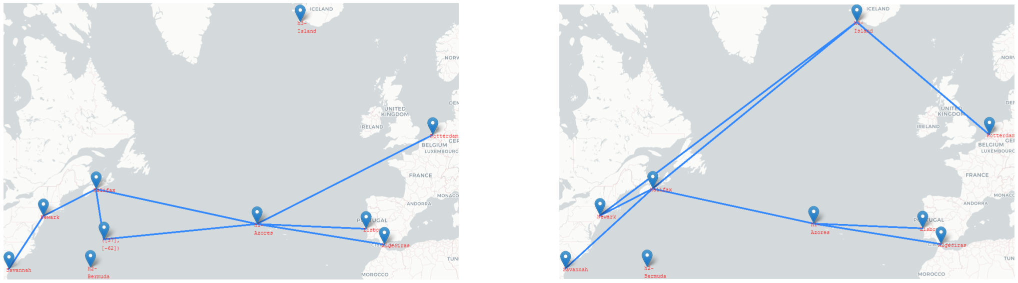
Table 5.16: Energy replenished by location

Vessel	$C^H = 0$		$2 \cdot C^H$	
	$k_v\ [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$	$k_v [m^3]$	$\sum_{i \in N} q_{iv}\ [m^3]$
1	-33%	-5%	+2%	+3%
2	-33%	-5%	+2%	+2%
3	-33%	-6%	+2%	+3%
4	-22%	-1%	+5%	+1%
5	-22%	-1%	+5%	+1%
6	-22%	-1%	+5%	+1%
7	-22%	0%	+5%	+1%
8	-22%	0%	+5%	+1%
9	-22%	-1%	+5%	+1%

Table 5.17: Resulting variables for the vessels with different cost of energy supply from the hubs

5.3.5 Variations in energy price

The price for energy supplied in port and supplied offshore affects the model decisions. Doubling the price in port gives the result shown in Figure 5.8a where the Azores supply hub establishes a energy replenishment station and another one is established in location (37,-62) with supply from Bermuda. If the price of energy supplied at the energy supply hubs should double the result can be seen in Figure 5.8b. For this case the energy supply hub on both the Iceland and Azores is established. In Table 5.18 the portion of energy supplied in the different locations for the different energy price scenarios is shown. In Table 5.19 the resulting energy storage capacity for the vessel sand the total energy replenished for the two scenarios is listed.



(a) $2 \cdot C^E_{port}$ **(b)** $2 \cdot C^E_{offshore}$

Figure 5.8: Connected nodes and selected energy replenishment station location for different lost opportunity cost

Node	$2 \cdot C^E_{port}$	$2 \cdot C^E_{offshore}$
Newark	10%	11%
Savannah	6%	11%
Halifax	33%	41%
Iceland		11%
Azores	37%	23%
Bermuda (37,-62)	14%	

Table 5.18: Energy replenished by location

Vessel	$2 \cdot C^E_{port}$		$2 \cdot C^E_{offshore}$	
	k_v $[m^3]$	$\sum_{i \in N} q_{iv}$ $[m^3]$	$k_v[m^3]$	$\sum_{i \in N} q_{iv}$ $[m^3]$
1	+2%	+3%	+40%	-5%
2	+2%	+2%	+11%	-3%
3	+2%	+18%	+11%	-4%
4	+5%	+1%	+5%	+1%
5	+5%	+1%	+5%	0%
6	+4%	+20%	+5%	+1%
7	+5%	+1%	+5%	+1%
8	+5%	+1%	+5%	0%
9	+4%	+18%	+5%	+1%

Table 5.19: Resulting variables for the vessels with variations in energy price in port and from supply hub

Chapter 6

Discussion

6.1 Results

The results from the case performed in section 5.3 emphasizes the need for more energy storage capacity compared to conventional vessels, one of the main challenges of implementing liquid hydrogen as an energy carrier for deep sea container traffic. The results show that the lowest required energy storage capacity is 18500 m^3. For conventional vessels in this size-range energy storage capacity can occupy from 7000 m^3 up to about 20000m^3 of space on the vessels, however in addition the liquid hydrogen solution requires additional space for storage systems such as insulation and rely on an energy replenishment station to be established.

6.1.1 Vessel speed

Increasing the vessel speeds gives an increase in energy consumption. In the model this leads to energy replenishment stations being placed more beneficially from the vessel point of view and eventually to more energy replenishment stops for the vessels. The relative required storage capacity and total replenishment amount increases with increased speed, although not equally for vessel speeds of 24 kn due to more energy replenishment stations being visited. Slow steaming is one way of reducing energy consumption and in turn required energy storage capacity.

6.1.2 Lost opportunity cost

The lost opportunity cost has a negative correlation with vessel energy storage capacity well illustrated when changing the value of C^{LOC}. Increasing C^{LOC} makes it more economical to establishing more stations in more vessel strategic locations and for the vessels to make more replenishment stops.

6.1.3 Cost of supply

Cost of supply equal to 0 can simulate independent energy replenishment stations generating their own power such as some of the concepts presented in subsection 2.4.3. This scenario means the establishment of stations far offshore is as costly as establishing one in an energy supply hub. The effect of this came through in the model with three offshore energy replenishment stations being established the furthest away from a supply hub for any of the cases in this thesis. In the opposite case with a doubling in the cost of supply only the energy hub station at the Azores was established.

6.1.4 Change in energy cost

The cost of energy or fuel powering ships is an important cost component for marine transportation. The energy cost scenarios presented show that the optimal solution is greatly affected by relative change in energy price in different locations. As to be expected when the cost of energy increases in port a larger portion of the energy replenished is done in offshore replenishment stations and the same can be seen for increase in energy price offshore where more energy is replenished in port.

6.2 Model

6.2.1 Model limitations

The model is limited by not taking time periods into account. For example reducing vessel speed would mean less transportation capacity within a given period for the vessel. Similarly visiting more locations for energy replenishment would imply a lost opportunity cost related to the reduction of container transportation capacity over the given time period because of time used for energy replenishment operations. Large container vessels normally perform bunkering operations while loading/unloading cargo.

Another simplification made that could if improved, give better decision support and more optimal real life solution is to use continuous locations for the energy replenishment stations and not discrete. For a vessel freely able to move to different locations this would give a better representation. On the other hand if the energy replenishment station is a fixed structure a discrete location like in the model would make sense.

The node positions are given to the model as longitude and latitude coordinates. To calculate the distance between the nodes the haversine formula is applied. This formula implies that the earth is a perfect sphere which is not the case. It also does not separate between land and ocean, resulting in shorter distances than what is actually the case for the vessel traveling the sea.

Linking the voyage cost directly to distance covered is a simplification that for an illustrative case can give reasonable results, but a time dependent voyage cost might be more realistic. This would also make additional stops in ports or energy replenishment stations less attractive.

6.2.2 Relevance and other applications

The marine industry will need to adopt new green energy carriers in the coming years. Overcoming their relative weaknesses to make them competitive against existing solutions will therefore be important. One drawback that many of the new green fuels have and specially liquid hydrogen (which is studied in the last case), is the relative low volumetric energy density and the large requirement for additional fuel storage systems not needed for the most prominent carbon-based fuels today. The model developed in this thesis seeks give decision support for one possible future solution, the establishment of multiple energy replenishment locations.

The area of application for the model is not limited to deep sea container traffic. It can just as well be used for the case of the Thor vessel presented in subsection 2.4.3 given a set of cruise vessels and their routes, with a vessel research area as a hub, where additional cost applies if the operation is performed far from their are of research and restricted by their rescue field responsibility.

6.3 Possible model expansions

The model could be expanded to include time periods. With time periods in the model one could consider the positions of the energy replenishment stations to be dynamic and let them fulfill a demand which can be fluctuating in both time and space. This would give a better representation of a real world problem in many cases. It is reasonable to assume that eg. an energy replenishment vessel could serve multiple locations within a given time period. Time periods would also better facilitate for using AIS-traffic data in the model.

Discrete position of energy replenishment for fixed stations can be deemed reasonable, but for a case where the station can be dynamic in position the discrete locations limits the models ability to represent a real scenario.

Different energy carriers have traits making them more suitable for certain routes and applications. The model could therefore be expanded to include the choice of optimal energy carrier for the vessels.

6.4 Uncertainty in input parameters

As introduced in the thesis the main focus has been given to the development of the model and the input parameters have therefore largely been based on expert opinion.

The routes selected for the transatlantic case have not been checked extensively with traffic data to check their container traffic connection and other routes may be more busy and more interesting to investigate.

The energy supply hub have been selected without thorough investigation into the obstacles that lay beyond energy price and the geographic location. While the possible locations for energy replenishment stations have been selected arbitrary in a geographic proximity to the energy supply hubs.

The fixed cost of visiting an energy replenishment station and the cost per distance unit form the energy hub serving the station may be very different depending on which chosen concept and location specific conditions. In this thesis the fixed cost of an energy replenishment station visit was more of an scaled to fit the traffic simulated.

Chapter 7

Conclusion and further work

Concluding remarks

Energy replenishment stations for zero-emission vessels represents one of many possibly enabling solutions for the green shift within maritime transportation. The tempo in which this transition needs to be done highlights the importance of research done to facilitate for good decision support.

The model developed in this thesis is able to select optimal replenishment location, the required energy storage capacity and the amount of energy replenished in each location for ships. The model is generic and can serve as a basis for further model development

The specific case study investigating transatlantic container routes using liquid hydrogen as energy carrier gave outputs that underlines the need for supportive solutions to make liquid hydrogen a viable and competitive option. Liquid hydrogen powered vessels require much more storage space for fuel than conventional vessels today. The results gave an estimated required energy storage capacity ranging from about 18500 m^3 to 71000 m^3 and the results includes energy replenishment stops en route. For a conventional container vessel of 8000 teu similar fuel capacity is around 11 000 m^3[46]. The results from the various scenarios tested on the model gave solutions that often deviated a lot from the base case. Good research into the input parameters will therefore be important for further usage of the model.

Using liquid hydrogen as energy carrier for deep sea shipping will in the current environment incur extra costs due to the need for more energy storage capacity, or income will be lower due to less space for cargo compared to conventional fuel. One alternative much argued now is to reduce vessel speed, however this will also affect the number of voyages possible per year and thereby reduce income.

Although the energy replenishment stations in the form discussed in this thesis, some of which being placed far out at sea may seem like a distant idea in the present, it may become part of a larger network of transforming ideas for the future. The success of zero-emission technology within maritime transport relies on a sound foundation of research and investigation into possibilities, challenges and disruptive concepts.

Further Work

Research into how the replenishment operations are to be performed at the energy replenishment stations is an aspect not covered in this thesis. Future work could therefore include feasibility studies and implications for the model of using different types of energy replenishment stations. The location of possible energy supply hubs and energy replenishment stations is also a topic that could use more input such that locations can be deemed suitable or unsuitable.

The scalability of the model in this thesis is limited due to the formulation. Other formulations such as a heuristic approach could allow for a larger model environment and better overall decision support.

The model could be further expanded to include time periods as discussed. This would allow for better resource management overview and more realistic scenarios. Introducing AIS-data as a foundation for the vessels to be studied with the model is also a natural step.

In this thesis the parameters used in the different cases have been subject to large uncertainty. For some of the parameters this can be mitigated by more thorough research while other parameters are better modeled as stochastic. Nevertheless further usage of the scenarios described in this thesis should include more in depth study of zero-emission vessel parameters.

Bibliography

[1] UN, 'The paris agreement,' in 2015. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[2] IMO, 'Initial imo ghg strategy,' in 2015. [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx.

[3] ICS, *Shipping industry sets out bold plan to global regulator to deliver net zero by 2050*, Accessed: 10.06.2022, 2021. [Online]. Available: https://www.ics-shipping.org/press-release/shipping-industry-sets-out-bold-plan-to-global-regulator-to-deliver-net-zero-by-2050/.

[4] IRENA, 'Pathway to decarbonise the shipping sector by 2050,' 2021. [Online]. Available: https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050.

[5] G. Panagakos, 'Green corridors and network design,' in *Green Transportation Logistics: The Quest for Win-Win Solutions*, H. N. Psaraftis, Ed. Cham: Springer International Publishing, 2016, pp. 123–160, ISBN: 978-3-319-17175-3. DOI: 10.1007/978-3-319-17175-3_4. [Online]. Available: https://doi.org/10.1007/978-3-319-17175-3_4.

[6] Department of transport (UK), 'Cop26: Clydebank declaration for green shipping corridors,' 2022, Accessed: 15.05.2022. [Online]. Available: https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors.

[7] Nordisk råd og Nordisk ministerråd, 'Klarsignal om grønne skipskorridorer i norden,' 2022, Accessed: 15.05.2022. [Online]. Available: https://www.norden.org/no/news/klarsignal-om-gronne-skipskorridorer-i-norden.

[8] M. Joerss, A. Kersing, A. Kramer, M. Stone and D. Mohr, 'Green corridors: A lane for zero-carbon shipping,' *McKinsey Sustainability Report*, 2021, Accessed: 15.05.2022. [Online]. Available: https://www.mckinsey.com/business-functions/sustainability/our-insights/green-corridors-a-lane-for-zero-carbon-shipping.

[9] E. Fridell, 'Chapter 2 - emissions and fuel use in the shipping sector,' in *Green Ports*, R. Bergqvist and J. Monios, Eds., Elsevier, 2019, pp. 19–33, ISBN: 978-0-12-814054-3. DOI: https://doi.org/10.1016/B978-0-12-814054-3.00002-5. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128140543000025.

[10] IEA, 'International shipping - tracking report,' in Accessed: 20.05.2022, 2021. [Online]. Available: https://www.iea.org/reports/international-shipping.

[11] IRENA, 'Navigating to a renewable future: Solutions for decarbonising shipping, preliminary findings,' 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf.

[12] J. M. Bermudez and I. Hannula, 'Hydrogen - tracking report,' 2021. [Online]. Available: https://www.iea.org/reports/hydrogen.

[13] J. Holladay, J. Hu, D. King and Y. Wang, 'An overview of hydrogen production technologies,' *Catalysis Today*, vol. 139, no. 4, pp. 244–260, 2009, ISSN: 0920-5861. DOI: https://doi.org/10.1016/j.cattod.2008.08.039. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920586108004100.

[14] DNV, 'Comparison of alternative marine fuels,' 2019. [Online]. Available: https://sea-lng.org/reports/comparison-of-alternative-marine-fuels/.

[15] C. J. McKinlay, S. R. Turnock and D. A. Hudson, 'Route to zero emission shipping: Hydrogen, ammonia or methanol?' *International Journal of Hydrogen Energy*, vol. 46, no. 55, pp. 28 282–28 297, 2021, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2021.06.066. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319921022175.

[16] J. S. Carlton, R. Smart and V. Jenkins, 'The nuclear propulsion of merchant ships: Aspects of engineering, science and technology,' *Journal of Marine Engineering & Technology*, vol. 10, no. 2, pp. 47–59, 2011. DOI: 10.1080/20464177.2011.11020247. eprint: https://doi.org/10.1080/20464177.2011.11020247. [Online]. Available: https://doi.org/10.1080/20464177.2011.11020247.

[17] H. Schøyen and K. Steger-Jensen, 'Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications,' *Journal of Cleaner Production*, vol. 169, pp. 152–160, 2017, Experimentation for climate change solutions, ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2017.05.163. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652617311150.

[18] A/S BERGENS ELEKTRISKE FÆRGESELSKAB, '"beffen" – ferry across vågen, the bergen harbour,' 2022, Accessed: 05.05.2022. [Online]. Available: https://www.beffen.no/home/.

[19] O. B. Inal, J.-F. Charpentier and C. Deniz, 'Hybrid power and propulsion systems for ships: Current status and future challenges,' *Renewable and Sustainable Energy Reviews*, vol. 156, p. 111 965, 2022, ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2021.111965. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032121012302.

[20] Y. Peng, X. Zhao, T. Zuo, W. Wang and X. Song, 'A systematic literature review on port lng bunkering station,' *Transportation Research Part D: Transport and Environment*, vol. 91, p. 102 704, 2021, ISSN: 1361-9209. DOI: https://doi.org/10.1016/j.trd.2021.102704. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920921000109.

[21] D. Holden, 'Liquefied natural gas (lng) bunkering study,' 2014. [Online]. Available: https://www.maritime.dot.gov/sites/marad.dot.gov/files/docs/innovation/meta/9806/dnvlngbunkeringstudy3sep14.pdf.

[22] M. Spaniol, 'Offshore energy hubs,' *Periscope network*, 2020. DOI: 10.13140/RG.2.2.35492.50567.

[23] C. Thommessen, M. Otto, F. Nigbur, J. Roes and A. Heinzel, 'Techno-economic system analysis of an offshore energy hub with an outlook on electrofuel applications,' *Smart Energy*, vol. 3, p. 100 027, 2021, ISSN: 2666-9552. DOI: https://doi.org/10.1016/j.segy.2021.100027. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666955221000277.

[24] DNV, 'Floating substations: The next challenge on the path to commercial scale floating windfarms,' in Accessed: 11.02.2022. [Online]. Available: https://www.dnv.com/article/floating-substations-the-next-challenge-on-the-path-to-commercial-scale-floating-windfarms-199213.

[25] DEA, 'Denmark decides to construct the world's first windenergy hub as an artificial island in the north sea.,' in Accessed: 21.03.2022, Danish energy agency, 2021. [Online]. Available: https://en-press.ens.dk/news/denmark-decides-to-construct-the-worlds-first-windenergy-hub-as-an-artificial-island-in-the-north-sea-420532.

[26] ERM, 'Green hydrogen production at scale from floating offshore wind,' in Accessed: 21.03.2022, 2021. [Online]. Available: https://ermdolphyn.erm.com/p/1.

[27] ABB, 'The floating filling station: Bunkering zero-emission fuel at sea,' 2021, Accessed: 21.03.2022. [Online]. Available: https://new.abb.com/news/detail/46259/the-floating-filling-station-bunkering-zero-emission-fuel-at-sea.

[28] Shell, 'Major projects,' 2021, Accessed: 21.03.2022. [Online]. Available: https://www.shell.com/about-us/major-projects.

[29] C. Amante and B. W. Eakins, 'Volumes of the world's oceans from etopo1,' *National Centers For Environmental Information*, 2021, Accessed: 21.03.2022. [Online]. Available: https://www.ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html.

[30] C. Holst, 'Maersk supply service launches new venture company, stillstrom, to deliver offshore vessel charging,' *Maersk Supply Service*, 2022, Accessed: 15.05.2022. [Online]. Available: https://www.maersksupplyservice.com/2022/01/25/maersk-supply-service-launches-venture-company-stillstrom/.

[31] O. D. Henriksen, 'Offshore charging,' *Ørsted*, 2020, Accessed: 15.05.2022. [Online]. Available: https://offshore-publications.orsted.com/news/2020/11/offshore-charging.

[32] Ulstein, 'Ship design concept from ulstein can solve the zero emission challenge,' 2022, Accessed: 30.05.2022. [Online]. Available: https://ulstein.com/news/ulstein-thor-zero-emission-concept.

[33] F. S. Hiller and G. J. Lieberman, in *INTRODUCTION TO OPERATIONS RESEARCH*. McGraw-Hill Education, 2015, ISBN: 978-0-07-352345-3.

[34] M. L. Brandeau and S. S. Chiu, 'An overview of representative problems in location research,' *Management science*, vol. 35, no. 6, pp. 645–674, 1989.

[35] L. Zhen, S. Wang and D. Zhuge, 'Dynamic programming for optimal ship refueling decision,' *Transportation Research Part E: Logistics and Transportation Review*, vol. 100, pp. 63–74, 2017, ISSN: 1366-5545. DOI: https://doi.org/10.1016/j.tre.2016.12.013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1366554516304641.

[36] Z. Yao, S. H. Ng and L. H. Lee, 'A study on bunker fuel management for the shipping liner services,' *Computers & Operations Research*, vol. 39, no. 5, pp. 1160–1172, 2012, ISSN: 0305-0548. DOI: https://doi.org/10.1016/j.cor.2011.07.012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S030505481100205X.

[37] C. Wang and J. Chen, 'Strategies of refueling, sailing speed and ship deployment of containerships in the low-carbon background,' *Computers & Industrial Engineering*, vol. 114, pp. 142–150, 2017, ISSN: 0360-8352. DOI: https://doi.org/10.1016/j.cie.2017.10.012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360835217304801.

[38] X. Mao, D. Rutherford, L. Osipova and B. Comer, 'Refueling assessment of a zero-emission container corridor between china and the united states: Could hydrogen replace fossil fuels?,' 2020. [Online]. Available: https://www.researchgate.net/publication/344750654_Liquid_hydrogen_

refueling_infrastructure_to_support_a_zero-emission_US-China_container_shipping_corridor.

[39] E. Georgeff, X. Mao, D. Rutherford and L. Osipova, 'Liquid hydrogen refueling infrastructure to support a zero-emission u.s.–china container shipping corridor (working paper),' 2020. [Online]. Available: https://www.researchgate.net/publication/344750654_Liquid_hydrogen_refueling_infrastructure_to_support_a_zero-emission_US-China_container_shipping_corridor.

[40] R. Asariotis, G. Ayala, M. Assaf, C. Bacrot, H. Benamara, D. C. A. Cournoyer, M. Fugazza, P. Hansen, J. Hoffmann, T. Kulaga, A. Premti, L. Rodríguez, B. Salo, K. Tahiri, H. Tokuda, P. Ugaz and F. Youssef, 'Review of maritime transport 2021,' *The United Nations Conference on Trade and Development*, 2021. [Online]. Available: https://unctad.org/webflyer/review-maritime-transport-2021.

[41] L. Tavasszy, M. Minderhoud, J.-F. Perrin and T. Notteboom, 'A strategic network choice model for global container flows: Specification, estimation and application,' *Journal of Transport Geography*, vol. 19, no. 6, pp. 1163–1172, 2011, Special section on Alternative Travel futures, ISSN: 0966-6923. DOI: https://doi.org/10.1016/j.jtrangeo.2011.05.005. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0966692311000524.

[42] I. Dagkinis and N. Nikitakos, 'Slow steaming options investigation using multi criteria decision analysis method,' Jun. 2015.

[43] Full Avante News, *Container ship charter market rates*, https://fullavantenews.com/container-ship-charter-market-rates/, Accessed: 27.05.2022, 2022.

[44] Freightos Data, *Freightos baltic index (fbx)*, https://fbx.freightos.com/freight-index, Accessed: 26.05.2022, 2022.

[45] PwC, *The green hydrogen economy*, https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html, Accessed: 27.05.2022, 2022.

[46] FreightWaves, *How many gallons of fuel does a container ship carry?* https://www.freightwaves.com/news/how-many-gallons-of-fuel-does-a-container-ship-carry, Accessed: 10.06.2022, 2020.

Appendix A

A.1 Energy replenishment locations

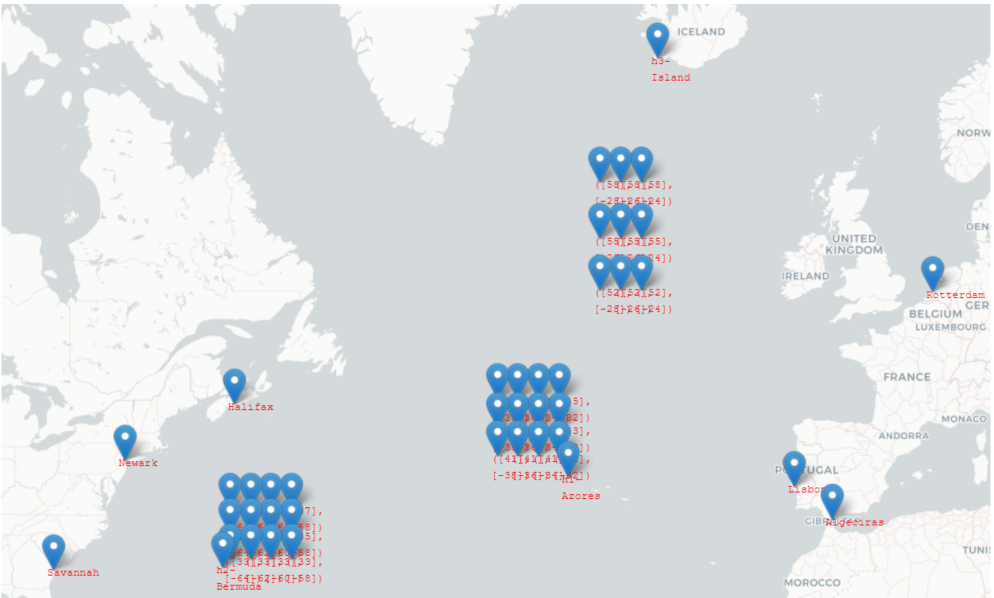
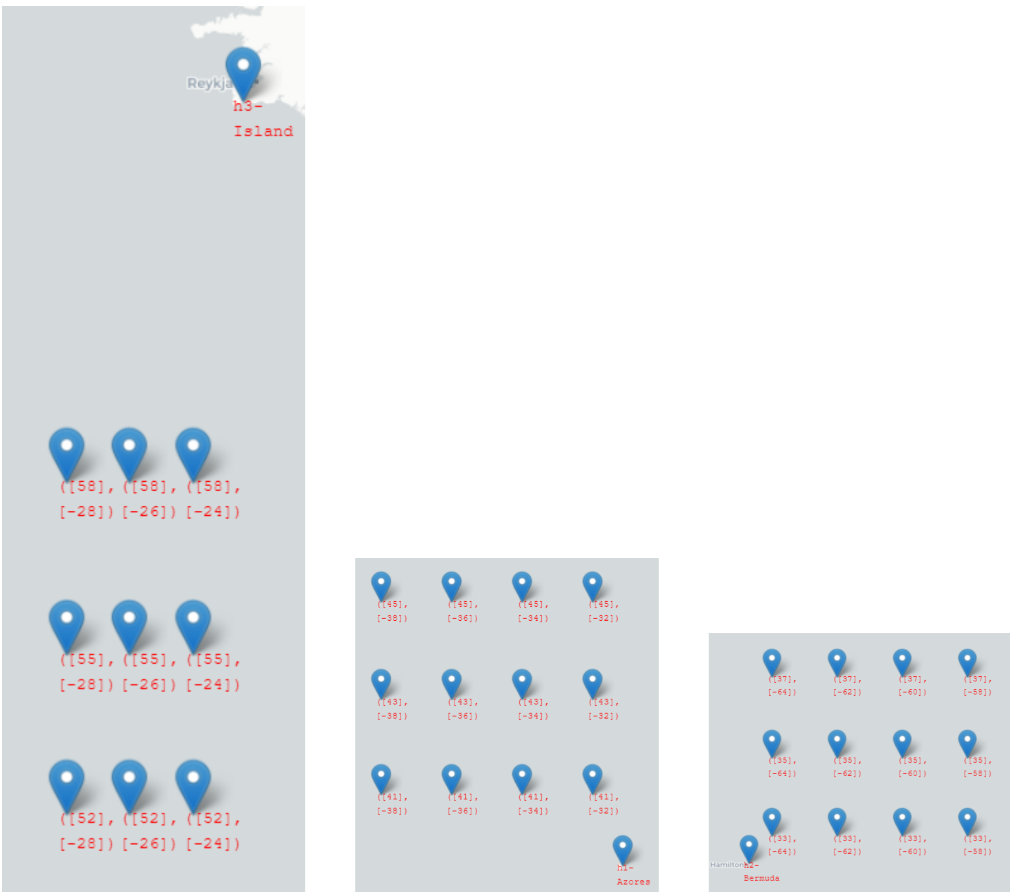


Figure A.1: Complete map of locations in the scenario

Azores	Iceland	Bermuda
(41,-32)	(58,-24)	(33,-58)
(43,-32)	(55,-24)	(35,-58)
(45,-32)	(52,-24)	(37,-58)
(41,-34)	(58,-26)	(33,-60)
(43,-34)	(55,-26)	(35,-60)
(45,-34)	(52,-26)	(37,-60)
(41,-36)	(58,-28)	(33,-62)
(43,-36)	(55,-28)	(35,-62)
(45,-36)	(52,-28)	(37,-62)
(41,-38)	(58,-30)	(33,-64)
(43,-38)	(55,-30)	(35,-64)
(45,-48)	(52,-30)	(37,-64)

Table A.1: Latitude and longitude coordinates of the possible energy replenishment locations having supply from their respective hubs. (lat,lon).



(a) Iceland **(b)** Azores **(c)** Bermuda

Figure A.2: Possible energy replenishment locations

A.2 Mathematical notation

	Sets
N	Set of nodes including O_v, the port of origin of vessel v and D_v, the port of destination for vessel v.
N^R	Set of possible energy replenishment locations including the hub H_j for each location, $N^R \subset N$.
A	Set of arcs between all nodes in N.
	Parameters
C_v^V	The voyage cost per distance unit for the vessel v.
C_v^{LOC}	Lost opportunity cost per unit of vessel v energy capacity.
C^H	The additional cost per distance unit from the energy-supply hub of operating an energy replenishment station.
C^S	The fixed cost of establishing an energy replenishment station.
C_i^E	Energy cost in location i.
K_v^V	Available space for cargo and energy storage in vessel v.
K_i^S	The maximum energy delivery capacity of energy replenishment station i.
F_v	energy consumption per distance unit with vessel v.
P^M	Factor accounting for portion of energy left as margin.
P^I	Factor accounting for additional portion of space needed for insulation and other systems to serve the energy storage system.
S_{ij}	Distance from node i to node j.
	Variables
k_v	Energy storage capacity of vessel v.
f_{ijv}	Energy consumption from node i to node j with vessel v.
u_j	1 if an energy replenishment station is opened in position j, 0 otherwise.
x_{ijv}	1 if vessel v travels from node i to j, 0 otherwise.
q_{iv}	Energy units replenished for vessel v in node i.
y_{iv}^A	Ship energy inventory when arriving at port i.
y_{iv}^L	Ship energy inventory when leaving port i.

Table A.2: Definitions

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