Master's thesis

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

Marit Solheim Thériault

Supply chain development and optimal location of reception points for shipboard carbon capture

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

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Det skapende universitet

Master Thesis in Marine Systems Design for

Stud. techn. Marit Solheim Thériault

"Supply chain development and optimal location of reception points for shipboard carbon capture"

Spring 2022

Background

The attention toward decarbonization of the shipping industry persists to increase. On-board CCS systems can play an essential role in meeting the emission target for maritime transportation and is regularly sought-after technology. Hence, it can be beneficial to study how on-board carbon capture systems and the development of relevant infrastructure can be developed. The location of reception points for the captured CO_2 will be relevant to evaluate for the development of sufficient infrastructure.

Overall aim and focus

The overall aim of the master thesis is to develop the logistical aspects needed for carbon capture as a shipboard application to decarbonize the shipping industry. The focus will be on logistics and infrastructure aspects, developing a supply chain and an optimization model that generates optimal locations of reception points for shipboard carbon capture

Scope and main activities

The candidate should presumably cover the following main points:

1. *A brief presentation of carbon capture and storge supply chain and technologies*
2. *A review of carbon capture and storage for shipboard application*
3. *Present relevant methods within operation research and applicable optimization models for carbon capture and storge infrastructure design and optimal location of reception points*
4. *Develop basic principles for a mathematical formulation to find optimal location of reception points.*
5. *Describe and discuss relevant extensions*
6. *Develop an extended mathematical formulation for the entire supply chain concept and location model*
7. *Discuss and conclude*

Modus operandi

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

Stein Ove Erikstad
Professor/Responsible Advisor

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Preface

This Master's thesis concludes my Master of Science in Marine Technology specializing in Marine Systems Design and Logistics at the Norwegian University of Science and Technology (NTNU). The work is conducted in its entirety by the author and has been carried out during the spring semester of 2022.

The thesis is a continuation of the specialization project from the fall semester of 2021, and parts of the work is based on this project. This mainly concerns a review of carbon capture technologies, the status of carbon capture as shipboard application and the development of a proposed supply chain. This master thesis extends the review of shipboard carbon capture by examining optimal location of reception points for a shipboard carbon capture supply chain.

I would like to thank my academic supervisor, Professor Stein Ove Erikstad from NTNU, for providing valuable guidance and insight throughout the entire thesis period. He has helped me seeing the big picture in the development of my work.

Lastly, I am grateful for my co-students for a great environment and insightful discussions regarding my thesis throughout the semester.

Trondheim, 9th June 2022

Marit Solheim Thériault

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Abstract

The International Maritime Organization (IMO) has defined mandatory measures to reduce greenhouse gas (GHG) emissions from international shipping, which accounts for 3% of the world emissions. The majority of the vessels in operation today, as well as those in current and planned production are expected to be equipped with combustion engines running on fossil fuels, and as such, the industry will be dependent on fossil fuels for decades to come. Carbon capture can therefore be important in decarbonizing the maritime industry. Onboard carbon capture and storage (CCS) systems can, due to their already high maturity for onshore applications, play an essential role in meeting the emission target for maritime transportation.

This master thesis aims to develop logistical aspects needed for carbon capture as a shipboard application to be an attractive and implementable technology to decarbonize the shipping industry. Existing research on carbon capture (CC) onboard ships is mainly related to feasibility studies, concept design, technical possibilities and development. However, the technological aspects are not the only ones to be in place to make the technology implementable. Infrastructure, supply chains, and logistics must also be developed to make carbon capture an attractive technology to decarbonize maritime transportation.

To address these aspects, this thesis investigates different carbon capture methods, and based on previous studies, gives an overview of suitable technologies for shipboard carbon capture. The main challenges related to carbon capture as a shipboard application is further addressed. The second part of the thesis presents a proposed supply chain for shipboard carbon capture. A mathematical optimization model based on the supply chain is developed to address the infrastructural challenges, and generate optimal locations of CO_2 reception points for shipboard carbon capture. The model is applied to a generated case study in the North Sea visiting four ports and a total distance of 2095 km. A parameter study is conducted with the case and model, and the results indicates that two reception point should be established along the route. The model development and results validates the importance of implementing CO_2 tax pricing on emissions in order to create real incentives to develope sustainable solutions and infrastructure to decarbonize the shipping industry.

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Sammendrag

Den internasjonale sjøfartsorganisasjonen (IMO) har definert obligatoriske tiltak for å redusere klimagass-utslipp fra internasjonal skipsfart, som står for 3% av verdens utslipp. Flertallet av fartøy i drift i dag, samt fartøy i nåværende og planlagt produksjon forventes å være utstyrt med forbrenningsmotorer som benytter fossilt brensel. Som sådan vil næringen være avhengig av fossilt brensel i flere tiår fremover. Karbonfangst kan dermed være betydningsfullt for å dekarbonisere den maritime næringen. Systemer for karbonfangst og lagring ombord på skip kan, på grunn av deres allerede høye modenhet for landbaserte systemer, spille en viktig rolle for å oppfylle utslippsmålet for sjøtransport.

Denne masteroppgaven tar sikte på å utvikle nødvendige logistiske aspekter for at karbonfangst ombord på skip skal være en attraktiv og implementerbar teknologi for å dekarbonisere shipping industrien. Eksisterende forskning på karbonfangst ombord på skip er hovedsakelig knyttet til mulighetsstudier, konseptdesign og tekniske utvikling. Teknologiske aspekter er imidlertid ikke det eneste som må være på plass for å gjøre teknologien implementerbar. Infrastruktur, forsyningskjeder og logistikk må også utvikles for å gjøre karbonfangst til en attraktiv teknologi for å dekarbonisere sjøfart.

For å adressere disse aspektene, har oppgaven vurdert ulike karbonfangstmetoder, og basert på tidligere studier, gir den en oversikt over egnede teknologier for karbonfangst ombord på skip. Hovedutfordringene knyttet til implementering av karbonfangst på skip er diskutert. Videre presenteres en foreslått forsyningskjede for CO_2 fanget ved hjelp av det implementerte karbonfangstsystemet. En matematisk optimeringsmodell basert på forsyningskjeden er utviklet for å møte de infrastrukturelle utfordringene, og finne gunstige plasseringer av mottakspunkt for CO_2 fra karbonfangst ombord på skip er generert. Modellen er benyttet på et generert case i Nordsjøen som besøker fire havner med en total avstand på 2095 km. Det er gjennomført en parameterstudie ved bruk av optimerings modellen og verdier fra casen. Resultatene tilsier at det bør etableres to mottakspunkter langs ruten. Utviklingen av modellen og resultatene validerer viktigheten av å implementere avgiftsprising på CO_2 utslipp for å skape reelle insentiver for å utvikle bærekraftige løsninger og infrastruktur for å dekarbonisere shippingindustrien.

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Acronyms

CC carbon capture. v, xiii, 2–4, 6, 11–13, 15

CCS carbon capture and storage. v, xiii, 2, 3, 5, 6, 9–14, 16–19, 27–30, 32, 33, 52, 59, 67

CCU carbon capture and utilization. xiii, 5, 6, 10

DNV Det Norske Veritas. xiii, 1, 2, 11, 12

EOR enhanced oil recovery. 13, 30, 51

FLP facility locating problem. 20, 21, 24, 25

GHG greenhouse gas. v, 1, 5, 10

ICE internal combustion engine. 15, 16

ICS International Chamber of Shipping. 18, 59

IMO International Maritime Organization. 1, 2

IPCC Intergovernmental Panel on Climate Change. 1

RP reception point. 35, 36, 42

SPP shortest path problem. 20–22

TRL technology readiness level. xv, 11, 14–16

UN United Nations. 1

VRP vehicle routing problem. 20–24

Chapter 1

Introduction

Climate change, specifically CO_2 emissions and its impact on our planet has been a hot topic for over a decade, and its importance will only increase as the measures already implemented do not seem to balance our consumption and emissions. In the summer of 2021, the IPCC (Intergovernmental Panel on Climate Change) of the United Nations (UN) published their report addressing a "code red" for humanity, which has led to increased focus on reduction in global CO_2 emissions [1]. Measures to mitigate climatic impacts are included into the majority of industrial and business strategies, including the shipping industry.

The international shipping industry plays a central role in global supply chains and accounts for more than 80% of global trade by volume. With this, the industry accounts for 3% of the world emissions [2]. In 2018 the International Maritime Organization (IMO) adopted a strategy of reducing at least 50% of the total annual greenhouse gas (GHG) emissions from international shipping by 2050 compared to 2008 [3]. This strategy has led to increased efforts to introduce decarbonization technologies and their applications to multiple aspects of the industry: alternative fuels, energy efficient design, operational aspects, sensor emission monitoring, and more efficient logistics and supply chains. Some measures can be applied to already existing ships, while others need to be considered in the design phase of the vessel.

From Det Norske Veritas's (DNV) report *"Maritime Forecast to 2050"* [4] published in the fall of 2021, it is clear that the industry will be dependent on conventional vessels for years to come. Today the world fleet consists of 99,5% ships running on conventional or so-called fossil fuels [4]. Additionally, as we see from Figure 1.1, the majority of ships being built in the upcoming years are expected to be equipped with combustion engines running on fossil fuels. Only 12% of ships on order in 2021 have alternative fuel engine systems.

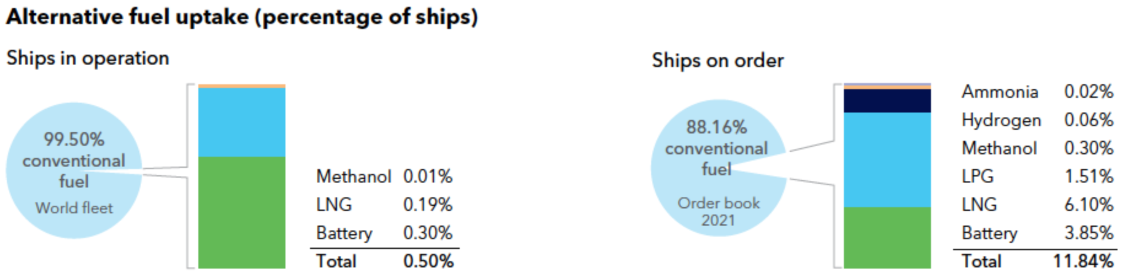


Figure 1.1: Uptake of alternative fuels for the world fleet as of June 2021 including ships in operation and on order, *provided by DNV* [4].

With the alternative fuel uptake presented by DNV [4], and by also taking into account that vessels have an average lifetime of 25-30 years, it is clear that the shipping industry will be dependent on fossil fuels for many years to come. If we assume that zero-carbon ships will be available from 2030, about 80% of the committed emissions will be from the currently existing fleet, not from vessels built throughout the next decade [5]. Hence there is particular focus on reducing emissions from the already existing fleet and not only to rely on replacing conventional ships with new and more efficient low-carbon ships [5].

Consequently, it is interesting to address alternative solutions for reducing the carbon intensity in shipping. Instead of neutralizing the emitted carbon emissions by, for instance, introducing new zero-carbon vessels, the exhaust gases can be filtered and the carbon removed from the exhaust gas with the technology recognized as carbon capture and storage. Carbon capture (CC) as a shipboard technology can thus be a crucial tool for achieving IMO's emissions targets.

1.1 Background

Carbon capture and storage (CCS) has for several years been highlighted as an essential technology to reduce emissions within several industries. The technology has been in commercial application in the power sector for more than 45 years [6]. It incorporates different technologies that prevent substantial amounts of CO_2 from being emitted into the atmosphere from the combustion of fossil fuels. In recent years, its application for other industrial sectors has been in the spotlight. The CO_2 emissions can for these sectors be a result of combustion, as well as chemical reactions and pre-combustion processing [7].

The storage of CO_2 has been seen as applicable both onshore and offshore. In recent years, different oil companies have seen the opportunity to enter this marked and are developing projects where CO_2 will be injected into mature oil fields. For offshore industries, an example is the Northern Light project of Equinor, Shell and Total, where they have decided to invest in the storage of CO_2 on the Norwegian Continental Shelf [8]. Combining CO_2 capture technologies with storage options in different underground and deep-sea areas can lead to negative lifecycle emissions while reducing emissions at the source in many different industries.

In recent years carbon capture as a shipboard application has raised attention as a solution to decarbonize the shipping industry, but this has mostly been discussed in theory [9]. However, projects related to the trial of this in practice have emerged, with several shipping companies seeing this as a solution to retrofit their already existing ship to reduce emissions and be in line with their customers' criteria for green shipping. There are however difficulties with implementing carbon capture (CC) as an onboard ship application. Space and weight are two critical factors for defining the value of a vessel, as the value is defined by its ability to transport cargo. These parameters are also heavily related to CCS as the volume of CO_2 increases by a factor of 3 after combustion. Additionally, the establishment of CO_2-handling infrastructure in ports will need to commence if CCS onboard vessels is to become an attractive solution in the maritime industry.

1.2 Master thesis objective

The main objective of this master thesis will be to propose and develop logistical aspects needed for carbon capture as a shipboard application to be an attractive and implementable technology to decarbonize the shipping industry.

To meet the main objective, sub objectives are defined. Firstly, it will be important to develope a supply chain for the shipboard captured CO_2 while incorporating exciting infrastructural aspects. The focus will further be to step-wise develope an optimization model that generates optimal location of reception points for shipboard carbon capture based on the proposed supply chain and with this gaining an understanding of how shipboard carbon capture and related infrastructure best can be implemented.

1.3 Scope and limitations

The specific tasks for the thesis are as follows:

1. Review the status of carbon capture and storage as shipboard application.
2. Propose an infrastructural supply chain for shipboard carbon capture and discuss its different aspects .
3. Develop a simple mathematical formulation to find optimal location of reception points based on vessel route and predefined locations.

4. Extended the simple mathematical formulation to include the entire supply chain concept and a location optimization model.

However, there are some limitations to the development of the supply chain and optimization model. The proposed supply chain will solely be generated in regards to the captured CO_2 onboard the vessel and its further distribution. This implies that operational aspects related to the vessel activity and cargo handling will not be included or considered throughout the thesis.

1.4 Structure of thesis

The project thesis starts with providing a quick background overview and introduction for the project and master thesis in chapter 1. The supply chain of carbon capture and storage and the different available technologies are described in chapter 2. Further, the status, technological maturity, development, and challenges related to carbon capture as shipboard application are described in chapter 3. In chapter 4 relevant operation research theories and optimization models are presented. The thesis moves on to discuss the infrastructural aspects of shipboard carbon capture in chapter 5 by proposing and describing a supply chain for the implementation of carbon capture in the shipping industry. In chapter 6 an initial optimization model presenting the base characteristics and main concept of the proposed supply chain is developed, finding the optimal location of CO_2 reception points based on vessel operation and predefined points. The model is further extended in chapter 7 to include the downstream logistics of the supply chain and possible carbon taxes. A case study utilizing the developed model, based in the North Sea is conducted in chapter 8. Lastly the supply chain, model and case results are discussed in chapter 9 before the thesis is concluded in chapter 10.

Chapter 2

Carbon capture supply chain and technologies

2.1 Main steps of the supply chain

Carbon capture and storage (CCS) is recognized as a series of techniques applied in order to separate CO_2 from fossil fuels in power plants or industrial processes, transporting the compressed CO_2 using ships or pipelines and further injecting it into geological strata onshore or offshore for permanent storage. Related technologies are becoming more mature, effective, and in higher demand. Large industrial facilities and power plants are starting to take advantage of the technology to reduce or even eliminate its carbon footprint. According to the Global CCS Institute [10] there were in 2021, 27 operational CCS facilities worldwide as well as 102 facilities in development. This further enhances the major investments that are being made within this technology and the dedication to reduce GHG emissions.

Generally, CCS involves three main steps: capture, transportation, and storage. In some cases, the captured CO_2 is also utilized in different production and service industries instead of being stored. This process is known as carbon capture and utilization (CCU). The supply chain for both carbon capture and storage and for carbon capture and utilization is illustrated in Figure 2.1

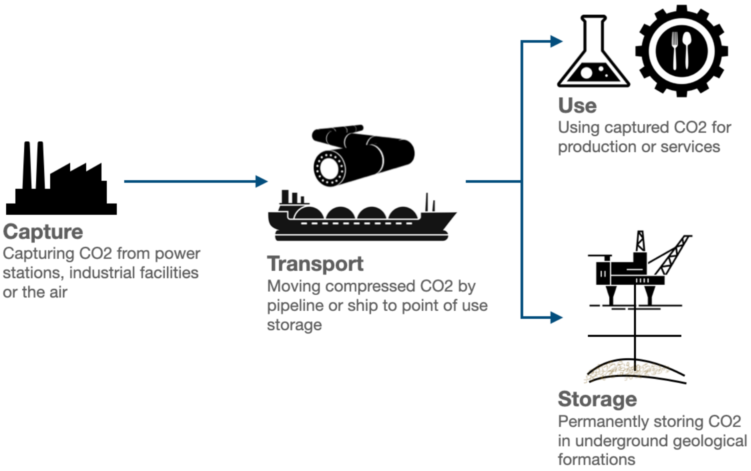


Figure 2.1: Supply Chain for CCS/CCU

In the following sections, the different steps of CCS will be further described, including some overall capture methods widely applied in power plants: pre-combustion capture, post-combustion capture, and oxyfuel combustion capture.

2.2 Carbon capture and storage technologies

2.2.1 Methods to capture carbon

The capture of CO_2 is the first step in CCS, and hence an important technology to prevent large amounts of CO_2 being emitted to the atmosphere. CO_2 is separated from fossil fuel or exhaust gas produced at large-scale industrial facilities such as coal and natural-gas-fired power plants, steel mills, fertilizer factories, and during the manufacturing of industrial materials such as cement, iron, steel, and paper [6]. Energy from fossil fuels are released in the combustion process at these facilities, which results in the emission of CO_2 as a by-product. Technologies for separating and capturing CO_2 have been operational in the natural gas and fertilizer industries for decades and have only recently become operational in the power sector [6].

Generally, we can distinguish between three different carbon capture (CC) methods for capturing CO_2 from a source: pre-combustion, post-combustion, and oxyfuel combustion capture.

Pre-combustion capture

In pre-combustion capture, as the name implies, CO_2 is separated from the fuel before an energy conversion occurs. The fuel is converted into a gaseous mixture (syngas) of hydrogen and highly concentrated CO_2. The hydrogen is further separated and can be combusted in a hydrogen gas turbine and from there produce electricity without producing any CO_2 [6].

The most common method used to capture CO_2 in pre-combustion are absorption with chemical absorbent or condensation method [11]. A process overview of pre-combustion capture is illustrated in Figure 2.2.

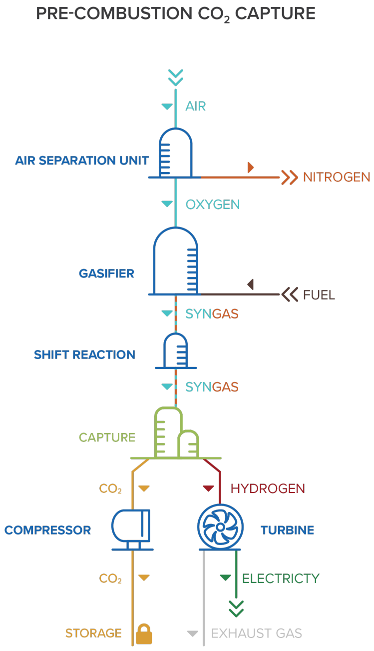


Figure 2.2: Pre-combustion capture system, *provided by Global CCS Institute [12]*

The fuel conversion process required for pre-combustion is quite complex and requires a significant initial investment for the system's design, building, and integration. This makes the method challenging to apply to already existing facilities, and therefor a better solution for new build projects than for retrofitting. However, the method has high efficiency and can capture 90%-95% of CO_2 from the fuel oil [11].

Post-combustion capture

Post-combustion capture separates the CO_2 from the exhaust gas after the fuel has combusted. In this method, the exhaust gas generally has a low concentration of CO_2 that arises from the combustion of hydrocarbons. The CO_2 can be captured from the exhaust gas with different methods, such as absorption by chemical or solid solvents, membrane technology, or cryogenic carbon capture [9]. Carbon capture by chemical absorption is the most mature and frequently used method amongst different post-combustion technologies. Once the chemical solvent absorbs the CO_2, heat is applied to release the CO_2 and form a high concentration CO_2 stream that gets compressed for further storage [6]. A general process overview of post-combustion capture is illustrated in Figure 2.3.

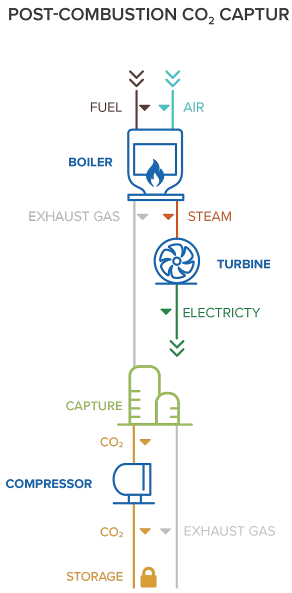


Figure 2.3: Post-combustion capture system, *provided by Global CCS Institute [12]*

Retrofitting is for post-combustion capture a more attractive solution than for pre-combustion, as the system is based on processes of exhaust gas treatments. The method further introduces the least amount of changes on facilities and is also the most mature method, as it has been used for at least half a century.

Oxyfuel combustion capture

Unlike pre-combustion and post-combustion processes, oxyfuel combustion uses oxygen instead of air for the combustion of fuel. This creates exhaust gas containing mainly CO_2 and water vapor that can further be easily separated to a highly concentrated CO_2 stream [6]. Figure 2.4 illustrates the process overview of oxyfuel combustion capture.

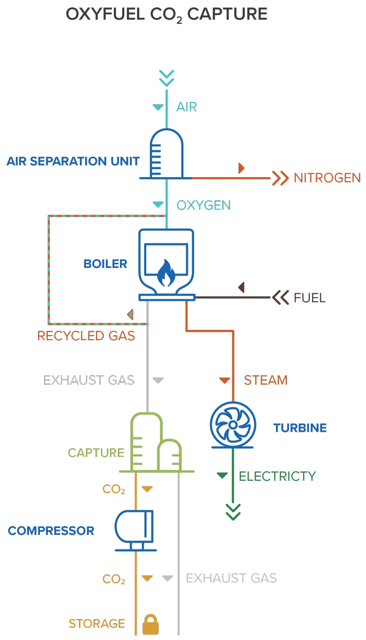


Figure 2.4: Oxyfuel combustion capture system, *provided by Global CCS Institute [12]*

The oxyfuel combustion process has extremely high efficiency with the potential of capturing 100% of the CO_2. Retrofitting to existing systems is also possible for the oxyfuel capture system as it does not affect the system remarkably. However, high temperatures in the different processes will demand higher material quality in several components, which will increase the cost of retrofitting. As the method is still in the development stage, only a few pilot power plant utilizes this method.

2.2.2 Transportation of carbon

The next step in CCS is the transportation of CO_2 by pipeline or ship to a location for storage or a facility where it can be utilized. Pipeline transportation is the cheapest and most commonly used option for transporting large quantities of CO_2 [6]. When pipeline transportation is not possible, for instance for longer distances overseas, transport by ship is often a better solution. Ship transportation of CO_2 at a large scale is still under development and has a lot in common with the shipment of liquefied petroleum gas where there already exists decades of experience [13]. Transportation by truck or rail is also used for small quantities onshore, but given the amount of CO_2 that will be captured with CCS this transportation method will most likely not play an important role.

Before transporting and storing CO_2, the gas must be either compressed or liquefied as CO_2 gas at atmospheric pressure is extremely large in volume. For pipeline transportation, compressed CO_2 is the chosen solution. For ship transportation, liquefied CO_2 is the better option as this leads to an even more significant reduction in volume than compressed CO_2 [14].

2.2.3 Carbon storage and utilization

The final step of CCS is geological storage of CO_2. Geological storage implies injecting the captured CO_2 in subsurface rock formations. With this technology, permanently removing it from the atmosphere reduces the world's greenhouse gas output. Globally there are many locations with the required characteristics to store CO_2 in the subsurface. This includes both depleted oils reservoirs but also in porous rocks more than 1 km below the subsurface, in deep saline formations that is sealed by a caprock for permanent storage [6].

The technology of natural storage of CO_2 in the subsurface has existed for a long time. Several geological systems naturally contain large quantities of CO_2 and have done so for thousands of years. In addition, the oil and gas industry has utilized CO_2 for decades in a process called enhanced oil recovery. This involves injecting CO_2 into oil reservoirs to increase reservoir pressure that again will improve the oil recovery from the fields [6].

Underground storage and enhanced oil recovery is not the only solution for what to do with captured CO_2. As mentioned previously, there is an increased focus on utilising the captured carbon. CCU includes technologies that combine captured carbon with further utilization and industry application. With this technology, carbon capture has the opportunity to develop into a circular economy solution [9]. The carbon can be transformed into a diversity of different value-added products, for instance synthetic fuels, chemicals, food, or materials [15]. The carbon can also be utilized in the agriculture industry as CO_2 enrichment in greenhouses allows crops to meet their photosynthesis potential [16].

Chapter 3

Carbon capture as shipboard application and the challenges

Having established and described the different carbon capture and storage technologies, this chapter will focus on how these technologies are considered implementable as shipboard applications and its' possible challenges through a literature review.

Research has until today mainly focused on the application of CCS onshore. The recent increasing interest in technically and economically feasible solutions to decarbonize the shipping industry has drawn interest to further development of carbon capture technologies onboard vessels.

Different studies and ongoing projects regarding carbon capture onboard ships will be presented in the following sections. In addition the technology readiness level (TRL) for ship application of the different technologies given in chapter 2 will be presented and evaluated, in order to identify how far the availability of the technologies has come for general usage. Lastly, the challenges related to shipboard CCS are addressed.

3.1 Status of shipboard carbon capture

Already in 2013, Det Norske Veritas (DNV) conducted a theoretical feasibility study on implementation of carbon capture and storage technology onboard large vessels [17]. At that time, CCS was still a relatively unproven technology, even for onshore usage in power plants. The idea of transplanting this complex system to a constantly moving, space-constrained vessel seemed very ambitious [17]. They modeled a hypothetical design and operation of a ship-based CCS concept, illustrated in Figure 3.1, that is highly similar to the concepts we see today. The carbon capture system is illustrated on the stern deck connected to the exhaust pipe, and the storage tanks are placed on the main deck. DNV's project set a solid foundation for the further development of the shipboard carbon capture concept in the future. After the study was completed, the question was further if the shipping industry was ready for such a radical and costly technology. [17].

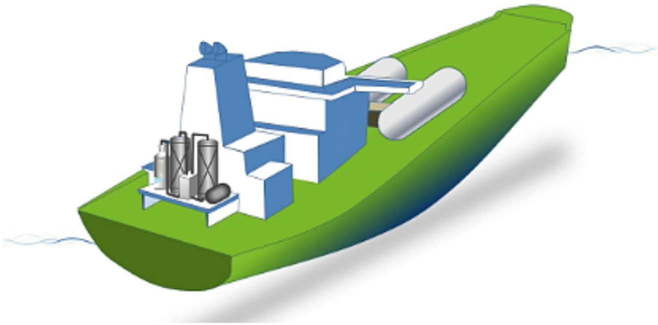


Figure 3.1: DNVs' hypothetical design for carbon capture onboard a vessel, *provided by ship-technology.com* [17].

Several scientific documents and theses have been written on the subject in the last decade. These include feasibility studies, case studies, and evaluations of economic feasibility, most of which have contributed to the development of the maturity for vessel application. Jonas Havenstein and Maximilian Weidenhammer from the Chalmers University of Technology, referenced earlier in this thesis, have evaluated the potential of carbon capture technologies for shipboard application with a review of them and their feasibility for onboard application [9]. They performed a comparative assessment of different carbon capture technologies to identify which is the most promising to apply onboard a vessel. They found that the most attractive technology for newbuilding and retrofit applications was post-combustion absorption. Additionally, they concluded that carbon capture and storage might be more feasible for larger vessels, based on evaluated transport capacity and economy-of-scale factors [9].

In recent years there has been an increasing emergence of projects and pilot tests of onboard carbon capture solutions. There has been a rapid development since DNV 's study in 2013, and several shipping companies are both committed to and investing in implementing fully developed carbon capture and storage technologies onboard their vessels in the next few years.

As an example, TECO 2030 has, together with Austrian-based automotive consulting firm AVL List GmbH, conducted a feasibility study where they concluded that onboard carbon capture and storage is technically and financially viable. With their technology, they claim that they can reduce CO_2 emissions by 30-40%, which would have a significant impact on the ship's Energy Efficiency Index (EEXI) and Carbon Intensity Index (CII)[18]. Further, the company intends to carry out a pilot development and test for maritime applications where the focus will be on verification and optimization [18].

Wärtsilä, together with the Norwegian shipping company Solvang, is further planning on installing a CCS system onboard the ethylene ship Clipper Eos within 2030, as illustrated in Figure 3.2. Similar to the DNV study from 2013, [17], the carbon storage tanks are placed on the main deck, and the capture system is connected to the exhaust pipe and combustion system. Their goal is to have their system capture 70% of the CO_2 from the exhaust gas. This will be dependent on available heat and energy as well as tank capacity for CO_2 [19]. The installation further shows that CCS technology is only two or three years away from being available on the shipping market.

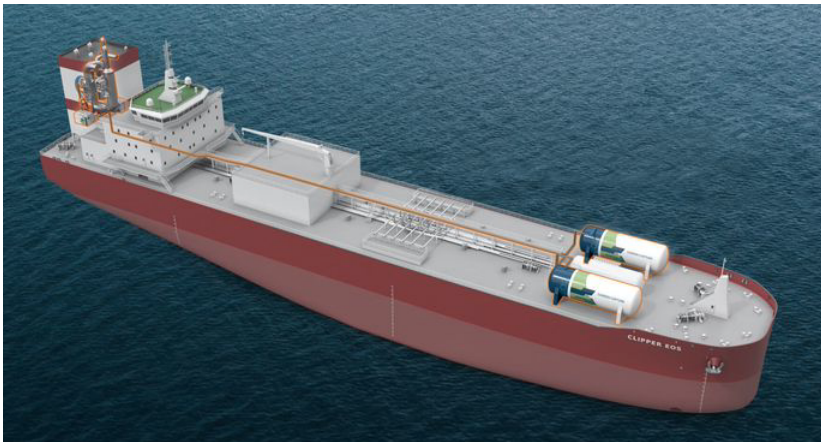


Figure 3.2: Wärtsilä and Solvang design for carbon capture onboard Clipper Eos, *provided by tu.no* [19].

A few companies have gotten far with testing their solutions onboard. During 2021 both Mitsubishi and Value Maritime installed carbon capture and storage technologies onboard a vessel. Value Maritime is a Dutch startup that provides modular gas-cleaning systems to ship owners [20]. They have now added the CCS technology to their already existing filter system that has previously separated sulfur and ultra-fine particulates from the exhaust gas. The technology is estimated to capture 100% of the CO_2 from the exhaust gas, and was retrofitted on a small container vessel operating in Europe during the fall of 2021. The captured CO_2 is discharged at greenhouses in the Rotterdam Area, which re-use the CO_2 to grow their crops [20].

In addition, Mitsubishi has started a demonstration test of a small carbon capture device on an 89,000 dwt coal carrier ship. The system is expected to capture the CO_2 with more than 99.9% purity [21]. With this installation, the company will evaluate the operation, safety, and operability of the system with the aim of commercializing the equipment. The captured CO_2 is expected to be utilized for enhanced oil recovery (EOR) processes or as raw material in synthetic fuels [21].

3.2 Technological maturity

In addition to the progression within shipboard carbon capture, the advancement and focus on carbon capture and storage technologies for onshore application has been in the spotlight for years. The increasing progression of new technologies, making CCS more efficient and less space-consuming, will highly benefit the development of CCS technologies onboard vessels, as it will make them easier to implement.

An acknowledged method to measure the maturity of a given technology or project is to evaluate its technology readiness level (TRL). This method was developed by NASA [22] and is used within many industries to map and assess the development and maturity level of new, emerging technologies. A technology or project is evaluated against the given parameters for each technology level and is then assigned a rating based on the project's progress [22]. The nine different TRL levels are presented in Table 3.1, where 9 is the highest maturity level and 1 is the lowest.

TRL	**Level**	**Description**
Deployment	9	Actual system proven in operational environment
	8	System complete and qualified through test and demonstration
	7	System prototype demonstration in operational environment
Development	6	Prototype demonstration in relevant environment
	5	Technology validation in relevant environment
	4	Technology validation in laboratory environment
Research	3	Analytical and experimental characteristic proof of concept
	2	Technology concept and/or application formulated
	1	Basic principles observed and reported

Table 3.1: Technology readiness level (TRL), [22]

In the following section, the maturity of different carbon capture and storage technologies will be briefly evaluated for shipboard application based on previously completed studies of Wang H. et al. [11] and Havenstein J. and Weidenhammer M. [9]. Only the technologies related to the technical aspects onboard the ship will be addressed, as these are the most compromising regarding implementation. This mainly applies to the capture, post-processing, and storage technologies. The TRL's of the different capture technologies will also be addressed in order to identify how far the availability of the technologies has come for general usage.

3.2.1 Methods for shipboard carbon capture

Pre-combustion capture

The pre-combustion carbon capture technology is in commercial use worldwide and has been used in industrial applications, for instance, gasification of carbonaceous fuels, for several years. This implies that it is highly mature for industrial application and has a TRL of 9 [9]. The technology has however not been applied in connection with an internal combustion engine (ICE), which reduces the TRL for this purpose. The general subsystem components for the technology have however been validated, which assign the pre-combustion capture technology a TRL of 5 for internal combustion engine (ICE) application [9].

For shipboard application, the technology is therefore not available for existing ships. The measures to retrofit a vessel with this technology would require significant changes in engine type to a hydrogen gas turbine, and installment of a reaction tank to convert the fuel to syngas, all of which would make it challenging and costly to install on an existing vessel [11]. The technology can however be a reasonable solution for new ships since the TRL is increasing for ICE application. A company called HyMethShip is currently developing a system that combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol, and a hydrogen combustion engine into one system, closing the CO_2 loop for the vessel [23]. This technology can be a promising solution for new and innovative zero-carbon ship design.

Post-combustion capture

Post-combustion capture is probably the most mature method. It is widely utilized in power plants and industrial processes, as it is the most economical method as it directly connects to the firing of fossil fuel in air [11]. As described in chapter 2 there are several methods to capture CO_2 post-combustion. Absorption by chemical solvents has the highest TRL with a level of 9. The other methods are still under development and vary between a TRL of 5 and 6 [9].

For ship application, post-combustion capture is the main technology used for the different projects that are currently emerging in the shipping industry. TECO2030, Wärtsilä, Mitsubishi, and Value Maritime are all utilizing and exploring methods related to post-combustion carbon capture. The implementation of this method does not require a change of fuel or fuel system and will be more attractive for a shipowner [9]. The system can additionally be combined with the current exhaust gas emission system onboard the vessel [11]. J. Havenstein and M. Weidenhammer furthermore conclude with post-combustion capture being the most promising for both newbuilds and retrofitting, after research, interviews with experts, and a comparative assessment of the different technologies [9].

Post-combustion capture by chemical absorption is today seen as the most feasible solution amongst the different post-combustion methods. It has low power consumption, advantages in connection with sulfurous fuels, and the maturity level of the technology is high. However, it is the method that has the highest space requirements compared to the other post-combustion methods [9]. This requirement is critical for shipboard application as it can affect the vessel's cargo capacity. The development of alternative methods will hence be important.

Oxyfuel combustion capture
The last capturing method has mainly been explored for the combustion of solid and gaseous fuels in power plants. Several projects have developed pilot plants using oxyfuel combustion capture, and with this obtaining the demonstration state with a TRL of 7. Similar to pre-combustion capture, oxyfuel combustion capture has not yet been applied to ICE's. This application of the technology is still under development and has hardly reached TRL 4 [9].

According to [9] there are currently no available publications presenting concepts for the application of oxyfuel combustion onboard vessels. The feasibility of the application has however been evaluated by Wang et al. [11], where they conclude that once the technology is ready for commercial use, it can potentially be applied onboard. There are however challenges related to the installment of the technology in addition to the issues addressed in chapter 2. If the technology is to be implemented on ships, the equipment must be installed in restricted sites due to safety measures related to the production and storage of large amounts of oxygen, which would be problematic for most shipowners. This method will most likely also be best fitted for newbuilds as retrofitting the technology would include converting the engine to propulsion powered by oxyfuel combustion.

3.2.2 Post processing and storage

After the CO_2 has been captured onboard the vessel, it must be post-processed and stored onboard. As mentioned in chapter 2 the transport of CO_2 in liquid phase is most common for ship application. This is due to the large reduction in volume for CO_2 from the gaseous phase to the liquid phase. The liquefaction of CO_2 is obtained by a combination of increased pressure and reduced temperature to compress the CO_2 in order to obtain a liquid phase [14]. The compression process further requires a considerable amount of energy which could influence the vessel's operation.

The CO_2 is stored in tanks onboard the vessel, where space is typically limited due to the maximization of cargo space. Most designs that have emerged in the previous years include cylindrical tanks onboard the ship deck, which does not limit cargo space for most vessels. For container vessels, on the other hand, the placement of the CO_2 tanks is more critical, as it will highly influence the vessel's cargo capacity. In *"Roadmap to Zero-Emission from International Shipping"* conducted by The Japan Ship Technology Research Association, a concept design for a carbon capture and storage solution for a container ship is presented [24]. The CO_2 tanks are in this design placed midship, under the deck, right above the keel. This will mainly be a feasible solution for newbuilds, as the necessary changes for an existing vessel are substantial. Value Maritime has, on the other hand, added these storage tanks on deck, closer to the capture system, in container sizes modules in order to simplify the further transportation of the CO_2 onshore [25], see Figure 3.3a and Figure 3.3b.

(a) Solution onboard, [25]

(b) Tank solution, [25]

Figure 3.3: Value Maritime CCS solution, *provided by Value Maritime* [25].

3.3 Challenges

New and innovative solutions often come with challenges, so also for carbon capture and storage technologies, especially when applied to new systems. Even though the development of the technology is rapidly advancing, there are still some apparent overall problems related to the implementation of CCS onboard ships. Several companies have ongoing projects related to CCS and are further beginning the process of implementing the technology onboard vessels, and it is hence important to address the remaining challenges. There are three clear aspects where problems arise: space requirements, cost, and infrastructure.

3.3.1 Space requirement

Transport of goods is typically the purpose of a vessel, and the value of a ship is therefore heavily dependent on the available cargo area and weight. Incorporating new systems, technologies, and storage solutions on a vessel will influence the valuable onboard space. Implementing CCS system on a ship requires, amongst other components, a gas treatment system, solvents for the capture process, and storage tanks for the captured CO_2. The less space consumed for the system's installation and CO_2 tanks, the more cargo can be transported, and higher revenue is achieved. Developing technologies that increase the system's efficiency and decrease the space needed for CO_2 storage will be important. This will also increase how attractive the solution is for shipowners.

3.3.2 Cost

Economic aspects will always be the main contributor to how a certain technology develops. Both investment and operational costs are important for a shipowner, and will determine the willingness to invest in a specific technology. Additionally, the cost of building onshore reception points for the captured CO_2 and additional infrastructure in ports and elsewhere has to be accounted for.

As carbon capture and storage systems for shipboard application are currently not commercially on the market, implementing the technology also leads to investing in its development, which may be quite costly. As the technology develops into a commercial product, the investment cost will decrease but might still be relatively high due to a still low maturity of the technology. Additionally, as long as it is economically favorable for shipowners to have and produce ships running on fossil fuels, the trend of ordering and producing conventional vessels will not change.

The International Chamber of Shipping (ICS) has recently proposed a global tax on CO_2 emissions from ships since the shipping industry is not covered by the national obligations in the Paris Agreement [26]. This proposal emphasizes the role shipping industry takes when it comes to reducing emissions. The CO_2 emissions must further be priced at a level that provides real incentives to cut emissions quickly. The taxes have to be proportionate and relate to the direct emissions from the ship. This will also give the shipowner a specific and clear value and illustration of how much would be saved, if CO_2 taxes are high, by implementing a CCS system onboard. It has to be economically beneficial to capture CO_2, the result of which will lead to quicker development of the technology.

3.3.3 Infrastructure

CO_2 infrastructure construction is another a crucial step in the development and advancement of carbon capture and storage as a shipboard application, and is also one of the main challenges frequently addressed concerning the implementation of this technology. The degree to which CCS is applied onshore will most definitely have a significant impact on the development of the infrastructure for transport, storage, and utilization of captured CO_2, which will further be a booster for CCS as shipboard application.

There are two main aspects of the infrastructural challenges. The captured CO_2 needs to be unloaded from the vessel once the CO_2 tanks onboard the vessel are full. The point of the unloading depends on the vessel size, speed, and storage tanks onboard and will not necessarily relate directly to the total distance to the ports on the vessels route, if all the CO_2 is to be captured. In the addressed projects from different companies the goal is to capture a certain percentage of the emitted CO_2, which in most cases will make it possible to travel directly to ports included in the vessels shipping route. In this way the percentage captured can depend on the distance traveled. However, if the problem is turned around one can claim that these unloading point should placed in a manner so that 100% of the CO_2 is captured. In this case it will be beneficial to obtain optimal location of these unloading points while keeping the lost opportunity cost of the vessel to a minimum. This specifically applies to container vessels that are volume critical. Furthermore, the captured CO_2 has to be transported to the point of utilization or injection. Combining these steps in a supply chain with already existing infrastructure for CO_2 onshore is believed to be beneficial.

3.4 Concluding remarks

This section has addressed different studies and projects related to carbon capture and storage as shipboard application, as well as identifying the ship maturation level and implementation of the different technologies. It has given a broad overview of the status of CCS in the industry and identified post-combustion capture as the most applicable solution as the technology is now.

Finally, some of the remaining challenges in regards to CCS onboard vessels were discussed: space requirements, cost, and infrastructure. This highlights important aspects of the technology and surrounding measures that need to be in place for sufficient implementation of the technology in a broader context.

Addressing technological challenges often leads to discovering gaps in the research area. Infrastructure for CCS is discussed in several studies and projects in regards to power plants and industrial facilities with further transport systems from facility to injection point or utilization. CCS onboard vessels is, however, not an included aspect or part of this supply chain. This makes the infrastructure and supply chain of CCS as shipboard application an interesting topic to do more research on, specifically finding optimal locations to unload the captured CO_2 and connect it with existing infrastructure.

Chapter 4

Methodology

The following chapter will briefly describe relevant methods within operations research that can be used for finding optimal locations to unload a vessels captured CO_2 before the infrastructural challenges will be more thoroughly described in chapter 5. When optimizing systems within the shipping and maritime industry, network optimization methods are frequently used. This includes shortest path problem (SPP), vehicle routing problem (VRP) and facility locating problem (FLP). As the main objective of this thesis is to optimize the location of CO_2 reception points, the facility location optimization models will be highly relevant. However, aspects and concepts of vehicle routing problem and shortest path problem will also be incorporated into developed models as these presents basic structures of optimizing maritime shipping problems.

All three optimization problems will be addressed in the following sections, together with the basis of operation research and network optimization, before a brief introduction of the chosen solver is presented.

4.1 Operation research

Operation research has played an essential role in modern history in, as the name implies, researching and improving operations within organizations. Hiller and Lieberman [27] defines operation research as a method applied within organizations to solve problems related to coordinating and conducting activities. Operation research has a wide breadth of applications and has been applied in areas such as transportation, construction, financial planning, the military, manufacturing, and public services.

The two main characteristics of operation research are its broad overview and attempt to search for an optimal solution for the problem that is considered [27]. It adopts an organizational point of view where the goal of the research is to identify the best possible approach in order to obtain the optimal solution for the organization as a whole while resolving conflicts of interest among the components of the organization.

4.2 Network optimization

Many optimization problems within operation research have a structure that can be described through a network problem, consisting of nodes and arcs. These problems can for example be related to transportation, distribution, electrical or communication networks that occur in several sectors of our daily life. This representation of a problem can also arise in areas like production, project planning, facilities location, resource management, supply chain management and financial planning [27]. The specific network structure is exploited in the solution algorithm and its wide application has been an accelerator for the solution methods. Network optimization models can be special types of linear programming or, if they include binary variables, they are referred to as combinatorial optimization problems [28].

Network problems can be divided into two main categories according to Lundgren and Rönnqvist [28]: how to utilize a given network in an optimal way and how to design a network in an optimal way. In the following sections the shortest path problem, which is defined within the first category of network problems, VRP and facility locating problem, that are defined within the second category, will be presented.

4.2.1 Shortest path problem

One of the most fundamental problems within network optimization is the shortest path problem, as it often appears as a sub-problem in more extensive network problems [28]. The objective of the problem is to find the shortest path from a given start node, n_s, to an end node, n_t, in a network in order to minimize distance, cost, time or other values that can be summed up over the arcs between the nodes in the network. A network solved as the shortest path problem has to satisfy the following, :

1. All arcs are directed
2. Node n_t can be reached from node n_s
3. There are no cycles with negative costs.

For the arcs to be directed they have to have an orientation, hence a directed arc only allows flows in a specific direction. Further a cycle is the definition of a connected sequence of arcs, starting and ending at the same node [28]. As SPP is a fundamental problem there exists several different algorithms to solve this type of problem, for instance Dijkstra's algorithm or Floyd-Warshall algorithm.

4.2.2 Vehicle routing problem

The vehicle routing problem (VRP) is a combinatorial optimization model that involves finding optimal routes for a fleet of vehicles visiting a set of locations. This model is highly used in maritime optimization, where shipowners have a fleet of vessels that have to visit and serve a demand or supply in specific ports. The model generates a network connecting the nodes in the system in an optimal manner.

The vehicle routing problem (VRP) model is an extension of the well-known traveling salesman problem. The aim is here for a salesman to find the shortest possible path for visiting all customers exactly once and then returning to his start node. For a VRP the costumers have a demand and are serviced by vehicles with a limited capacity which leads to the requirement for more than one vehicle. The vehicles start and end their round-trip in a depot, and all nodes are to be visited exactly once [29].

The VRP can be modeled similarly to a traveling salesman problem where all visiting nodes are taken into account in the model, or it can be modeled with pre-generated routes that are valid for the given restrictions, and that makes sure all nodes are visited [29]. In this section, the general VRP without pre-generated routes will be described. The formulation of the vehicle routing problem will in the following be presented, starting with the notations for the model.

Sets:
V = set of vehicles
N = set of nodes/costumers

Parameters:
C_{ijv} = cost of travelling between node i and j with vehicle v

D_i = demand at node i

K_v = capacity of vehicle v

Variable:

$$x_{ijv} = \begin{cases} 1, & \text{if vehicle } v \text{ is used on arc } (i,j) \\ 0, & \text{otherwise} \end{cases}$$

Vehicle routing problem:

$$min\ z = \sum_{i\in N}\sum_{j\in N}\sum_{v\in V} C_{ijv}x_{ijv} \tag{4.1}$$

Subject to:

$$\sum_{j\in N} x_{1jv} \leq 1 \quad \forall\, v \in V \tag{4.2}$$

$$\sum_{j\in N}\sum_{v\in V} x_{ijv} = 1 \quad \forall\, i \in N\backslash\{1\} \tag{4.3}$$

$$\sum_{j\in N} x_{ijv} = \sum_{j\in N} x_{jiv} \quad \forall\, i \in N,\ v \in V \tag{4.4}$$

$$\sum_{i\in N}\sum_{j\in N} D_i x_{ijv} \leq K_v \quad \forall\, v \in V \tag{4.5}$$

$$x_{ijv} \in \{0, 1\} \tag{4.6}$$

Equation 4.1 is the objective function of the model and minimizes the cost of the system modeled. The first restriction, Equation 4.2, further ensures that the vessels leave the depot no more than once at most, while the second restriction Equation 4.3 requires all nodes to be visited exactly once. Equation 4.4 is a flow conservation restriction and makes sure that all vessels going into a node also leave the node. Lastly, Equation 4.5 is the capacity constraint that requires the demand from the nodes that a vessel visit to be less or equal to the capacity of the vessel. Furthermore, the binary constraints are introduced in Equation 4.6. The model will also need sub-tour elimination constraints to ensure that it model does not construct routes between the nodes that do not visit the depot. These restrictions are however not given in the presented model.

This VRP model can further be extended to include several aspects of routing problems. These extensions can include the cost of using the vehicle, maximal duration of specific routes, time windows for the nodes to be serviced, and different capacity restrictions. The model itself is however the base for most routing optimization models within shipping.

Since alternative fuels have been a core focus in developing the shipping industry towards zero-carbon solutions, the vehicle routing problem has been developed to be adopted on alternative fuel vessels. This modification of the vehicle routing problem is referred to as green VRP and has been focused towards both road and water transportation. These models generally optimize a set of vehicle tours that minimize the total distance traveled to serve a set of customers, while incorporating stops at alternative fuel stations on the route to eliminate the risk of running out of fuel while maintaining low cost routes [30]. The models have been developed as a result of limited refueling infrastructure and the reduced driving range of most alternatively fuels vessels.

4.2.3 Facility location problem

A facility locating problem (FLP) is a classic optimization problem that can be utilized on several types of location optimization issues in different industries. It can for example be the location of a production facility, power plant, warehouse, or public transportation terminals. Such models are mostly connected to a demand from a certain area or user group in a given location, where the aim of the problems is to maximize the supplier's profit based on these parameters [31]. The literature related to facility location problems can be divided into single-, two- and multi-echelon problems. The single-echelon facility location problem includes production facilities, who's location is to be optimized, and end-costumers. The two- and multi-echelon problems on the other hand include one or several distribution centers before the product reaches its end-costumer, and can hence have several transportation links.

Lundgren and Rönnquist et al. [28] define a simple single-echelon as the problem of choosing a set of facilities m and from these, support a set of costumers n. Each facility i has a given capacity s_i, and each costumer j has a given demand d_j. The model relevan costs are the fixed capital cost f_i if facility i is constructed and the cost c_{ij} for each unit transportation between facilities i and customers j. The variables are defined as

$$y_i \quad = \quad \begin{cases} 1, & \text{if a facility } i \text{ is constructed} \\ 0, & \text{otherwise} \end{cases}$$

x_{ij} : number of units transported between facility i and customer j.

and the model can be formulated as

$$max\ z = \sum_{i=1}^{m} \sum_{j=1}^{m} c_{ij} x_{+} \sum_{i=1}^{m} f_i y_i \tag{4.7}$$

Subject to:

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

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

$$x_{ij} \geq 0, \qquad i = 1, ..., m; \; j = 1, ..., n \tag{4.10}$$

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

Equation 4.7 is the objective function of the facility problem, that aims to minimize the total cost. The total cost of the system is divided into transportation cost and capital cost. Equation 4.8 is the supply constraint that ensures that the transported number of units from a terminal does not exceed its given capacity. Equation 4.9 ensures that every costumer j receive its defined demand. Equation 4.10 and Equation 4.11 ensures respectively non-negativity for the variable x_{ij} and binarity for y_i.

As the usage area of this optimizing technique is wide, the basis of the technique has, amongst others, been used to further create models that optimize the location of refueling stations for alternatively fueled vehicles, which generally have a lower range than gasoline or diesel-fueled vehicles. Instead of locating central facilities to serve demand at specific locations as generally done in the FLP, the refueling location models aim to serve a demand consisting of flows from an origin to a destination (O-D) along its shortest path [32].

Studies and extensions done in relation to this type of model have mostly addressed onshore vehicle problems, and hence they consider large road networks. Ship routing problems can also develop to large networks but with different set of assumptions. For instance, vessels usually travel along a given route and will not have the same possibility to take a different path as onshore vehicles do. The simple model presented in this section can nonetheless be a good reference for developing a model generating optimal location for CO_2 reception points for shipboard carbon capture.

The facility locating problem has in recent years also been utilized as decision support to develop new infrastructure for alternatively fueled vessels. As mentioned previously vessels driven on alternative fuels generally have a shorter range then vessels running on conventional fuels. For deep sea shipping refueling hubs has therefore been considered as a solution. FLP has frequently been used as a tool to generate optimal locations of these hubs, as they will be expensive to establish.

4.3 Solver programs

Large optimization problems can become excessive and time consuming to solve without the use of digital tools. There are several digital solvers available on the market that easily solve defined problems if implemented correctly into the chosen software. Excel solver, Gurobi, Xpress and CPLEX are some of the most frequently used. The excel solver is implemented as a tool in excel while the three other mentioned solvers are compatible with several programming languages. For this thesis the developed optimization problem is implemented into Gurobi. Gurobi is one of the faster solvers for large, complex problems and can be utilized for all major problem types.

Chapter 5

Proposed supply chain and its challenges

So far, this thesis has focused on carbon capture and storage technologies, its status, implementation, and challenges for shipboard application. Relevant optimization models within operations research has further been introduced. The following sections move on to discuss in greater detail the infrastructural challenges described in the concluding remarks in chapter 3. Firstly a proposed supply chain for shipboard carbon capture is presented in order to gain a greater understanding of the system. The infrastructural problem of finding optimal locations of reception points to unload CO_2 from vessel is then described, in order to understand how to best model the problem.

5.1 Proposed supply chain

In order to grasp how the infrastructural problem can be defined, it is important to understand the relevant system as a whole. An important aspect here is the system's supply chain. A supply chain can be defined as an integrated process where several different business entities (suppliers, manufacturers, distributors, and retailers) work together to acquire and convert raw material into final products and further deliver these final products to retailers and end-costumers. A supply chain is generally characterized by a flow of material forward and a backward flow of information [33].

In chapter 2, a simple supply chain of carbon capture and storage for general industrial purposes was presented. This system has to be modified in order to represent the CCS process, production of CO_2, onboard a vessel and further delivery to an end-costumer. As the necessary infrastructure related to shipboard carbon capture is not fully developed, a proposed supply chain is presented in Figure 5.1 to further develop an infrastructural problem description. The supply chain here includes CO_2 as the flow of material. The chain consist of CO_2 production onboard vessels, reception points, transport of CO_2, and storage/utilization of CO_2 as end-costumer. The figure additionally indicates the supply chains upstream and downstream segments. However, the latter of which can be excluded if the reception point is located at an end-costumer. The system will include aspects and operations that might not currently be technically feasible. However, they are for this thesis assumed to be viable. In the following subsection the supply chain illustrated in Figure 5.1 will be presented in more detail. Figure 5.2 illustrates the supply chain for a simple transportation lap between two ports.

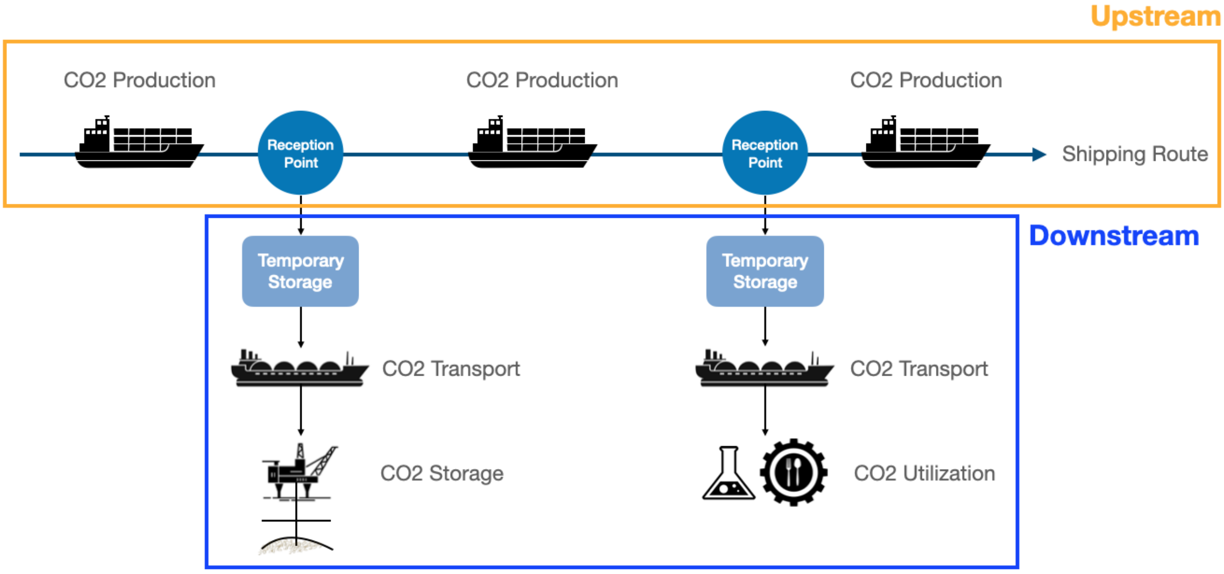


Figure 5.1: Supply chain for shipboard CCS

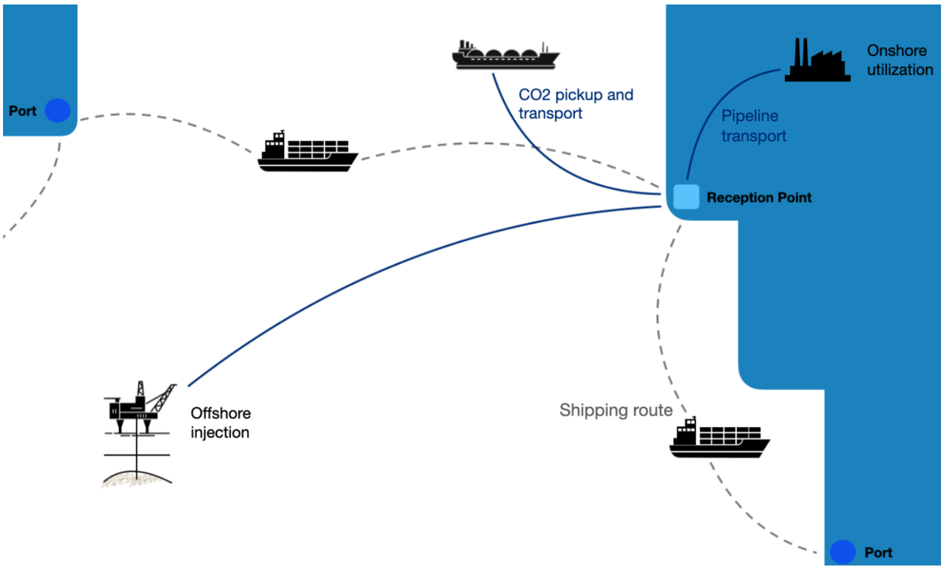


Figure 5.2: Map illustration of supply chain

The flow of CO_2 in the supply chain flows through the upstream, midstream and downstream segments from production to end-costumer. These segments will in the following be more thoroughly described.

5.1.1 Upstream

During the vessel's shipping route, CO_2 is captured from the exhaust gas produced by the combustion of fuel by a post-combustion capture method. The CO_2 will be compressed, liquefied, and stored in tanks onboard. The tanks can either be placed on the tank deck, in container sized modules for simple swapping of the tanks as presented in Figure 3.3, or under deck which is most applicable for newbuilds. These tanks will gradually fill up with CO_2 as the the vessel sails and combusts fuel. The tanks have to be emptied or swapped once or multiple times during the sailing route at an established reception point that is fit to receive CO_2. If the vessel sails with full CO_2 tanks, the CO_2 produced will be emitted to the atmosphere. Consequently, the vessels will have to stop at different reception points along the shipping route to unload the CO_2, if the supply chain is to be carbon free. This is a repetitive course of event between each reception point and is identified as the upstream segment of the supply chain. The frequency of available reception points will amongst others be based on the size of the vessel and CO_2 tank onboard.

5.1.2 Midstream

The midstream segment of the supply chain is not indicated in Figure 5.1, but is mainly identified as being the reception points where the upstream and downstream segments connect. The reception points along the route can be ports, depleted oil fields, CCS facilities in operation close to shore, or newly constructed reception points for the specific route. In Figure 5.1 these points are given as ports along the route or newly constructed reception points.

In reception points that are categorized as ports or so-called constructed reception points, the CO_2 will be temporarily stored in large tanks before the product is distributed to end-costumers. The CO_2 can either be unloaded from the vessel through pipes or by cranes if the CO_2 tanks are modular. However, reception points along the route can also be specific oil and gas platforms or CCS facilities in operation close to shore. For platforms, the CO_2 would be unloaded and directly injected into the oil and gas field either for the use of enhanced oil recovery or into adequate reservoirs. This reduces the supply chain and eliminates the extra transport leg in the downstream segment. The same accounts for a CCS facility in operation close to shore. The continued infrastructure would here already be in place, and it might only be necessary to build an unloading port.

5.1.3 Downstream

The downstream segment of the supply chain includes the distribution of CO_2 from reception point to end-costumer. As addressed in the description of the midstream segment, the downstream distribution will mainly be relevant for reception points that are based in ports or specifically constructed unloading ports. The CO_2 can here be temporarily stored in large CO_2 storage tanks, before being picked up by a CO_2 carrier and transported to a location for storage, or a facility where it can be utilized. If feasible, the CO_2 can also be transported by pipeline to a given location either offshore or onshore. The methods of transportation, storage and utilization of CO_2 were more thoroughly described in chapter 2.

The final stop in the generated supply chain is the end-costumers. These can be within be the agriculture sector, producers of synthetic fuels, or oil companies wanting to use the CO_2 for enhanced oil recovery, or invest in storing the CO_2 underground.

5.2 The challenge of modelling an optimal supply chain

As the supply chain is established, the problem description for the development of a supply chain model can further be developed. By assuming that carbon capture technologies are implementable onboard vessels, the main aspect of the supply chain that remains, to make the technology feasible, is the establishment of a good infrastructural system. This mainly involves establishment and decision support for where to locate reception points for an optimal operation of the vessels. The investment cost of building new unloading ports for the captured CO_2 will most likely be relatively high. Therefore, finding optimal location for reception points based on the route and ship type, while keeping the lost opportunity cost at a minimum and combining the model with exciting infrastructure will be essential.

Developing an infrastructural system for an entire industry is however a comprehensive task and defining the problem more specifically will be necessary. Firstly, the problem can be delimited by looking at the problem from different perspectives. Two perspectives will in the following section be discussed before implementation of the described supply chain is investigated by looking at existing infrastructure on a typical shipping route between Europe and Asia.

5.2.1 Perspectives

As CCS develops to a widespread technology to reduce emissions from different facilities and systems around the globe, the need for well functioning and efficient infrastructure for CO_2 will increase and be an essential part of the transformation towards zero-emission for several industries. Developing an infrastructure that is optimal for an entire industry is however a challenging task. Creating an optimization model demands for an objective, and creating one that grasps all infrastructural aspects is demanding. The objective or goal of creating a good model will differ depending on which stakeholder the model is solved in regards to. A shipping company would want to reduce costs as much as possible, whereas creating a model best suited in a global infrastructural manner would lead to a different objective. Two simplified perspectives will be defined in the following discussion in order to get an understanding of how to best approach the problem. For both perspectives, the cost of constructing new reception points will not be evaluated.

A shipping company's perspective

Firstly the problem can be evaluated from the perspective of a shipping company. The shipowner has the option of engaging vessels in either tramp or liner shipping. In liner shipping, the vessels regularly sail on a fixed route following a schedule, whereas vessels that do not follow a schedule or regular route are engaged in tramp shipping. The vessels can here carry a combination of contracted and spot cargo. The shipping perspective can also be generalized, where we assume that vessels travel between specific ports along the same routes. The routes can either be deep-sea or shorter routes.

The shipping company's objective will be to minimize their expenses and cost of the solution for reception point placement. With this objective function, the reception points will be located along the route based on vessel operation parameters and restrictions.A generated model will only evaluate where the vessels sail and not consider the surrounding infrastructural aspects. Evaluating an optimal location of the reception points from this perspective has the disadvantage of only including the shipping industry without considering other industries or existing infrastructure. On the other hand, modeling through this perspective will give a more straightforward model as it is more consistent, and can be a good starting point to develop a more complex model.

Global infrastructure perspective

Another perspective in which a location optimizing model can be established, is one that considers existing global infrastructure. Location optimization will in this case be based on pre-generated reception points along a certain route according to existing infrastructure. New reception points can also be established, but the location of these will be based on the further distribution of the CO_2 to existing infrastructure. The model will choose which reception points to unload the CO_2 based on ship parameters. In order to make the placement of reception points optimal in a global infrastructural manner, all main shipping routes will have to be taken into consideration, which will make the model difficult to solve. The objective function for a model with this global perspective perspective can somewhat vary. The perspective aims to include existing infrastructure into the model, and the objective function can hence be anything from cost to sailing distance minimization.

A more optimal model would include combining these two perspectives, consequently creating a more complex model. This would be a model based on optimizing location for the shipping industry while incorporating and optimizing for existing infrastructure. As pointed out earlier in this section, it will be beneficial to first establish a simple, idealized model that can be gradually extended to include additional aspects of the original problem.

5.2.2 Implementation with existing infrastructure

It can be beneficial to investigate how much available infrastructure exists along a specific shipping route on a broad level. This will help understand the extent of the problem and how then to solve it in a purposeful manner. It will also give a good perspective on how difficult it will be to develop the supply chain proposed in Figure 5.1.

In Figure 5.3, the main shipping route between Hamburg and Hong Kong is illustrated. Along the route, ports, large oil reservoirs, and CCS facilities in operation or development are highlighted. These points can be evaluated as possible CO_2 reception points for vessels sailing the route. The ports are placed in accordance with large and dominating shipping ports along the route, and the reservoirs are further placed based on the world's biggest offshore oil and gas discoveries most relevant for the chosen route [34]. The location of the CCS facilities in operation or development are based on data from the annual *"Global Status of CCS 2021"* conducted by the Global CCS Institute [10].

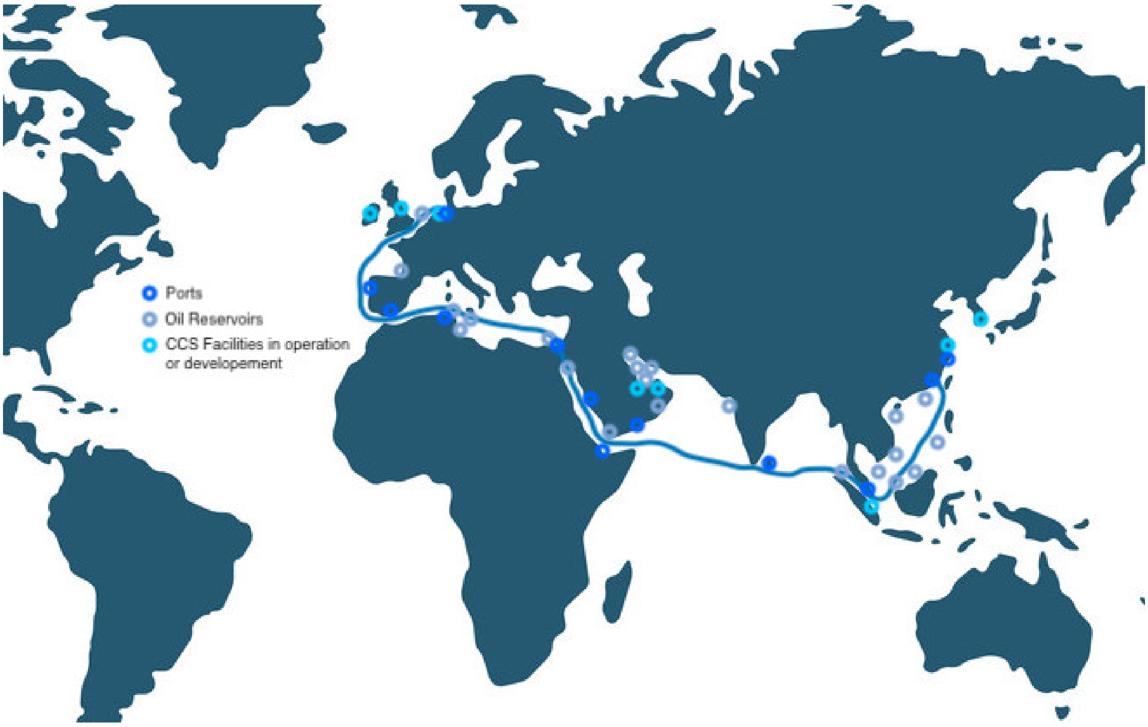


Figure 5.3: Shipping route with reception points

From Figure 5.3 we see that there are many possible reception points. Using these specific locations as reception points is based on the assumption that there is a higher probability for the development of CO_2 infrastructure in their vicinity. The infrastructure surrounding industrial facilities with implemented CCS technologies, both in operation and in development, will surely increase as this is necessary for the supply chain. As CCS technologies for shipboard application develops, several ports might be equipped with solutions to handle captured CO_2 and the remaining parts of the supply chain. Oil and gas reservoirs are also placed along the route; these are added with the assumption that it will be possible to unload the CO_2 tanks directly to an offshore platform, which can handle the further treatment and injection. Additionally, it can be assumed that there is a possibility to distribute reception points randomly along the route. Each point can refer to either a general area or a specific point with a port, oil field, or facility. Some areas have a high density of the given reception point type, which is simplified by only allocating one point.

In a generated model, the reception points can either be treated as the same without distinguishing between the infrastructural aspects available and at which reception points it is best to unload in regards to this, or they can be evaluated in correspondence to these exact differences. Some points will hence be more beneficial to unload at than others.

5.3 Concluding remarks

This chapter has presented a proposed supply chain for shipboard carbon capture. The supply chain is divided into upstream, midstream and downstream segments and described respectively which has given a thorough overview of the system. The discussion of the two perspectives also sets boundaries for how the optimization model can be formulated.

The chapter has given an introduction to the problem and a foundation for the model development. In the following chapter, firstly an initial model will be developed that only considers the upstream segment of the supply chain. The aim will be to find the optimal location of the reception while balancing the cost of establishing reception points and the lost opportunity cost onboard the vessel, generally taking the shipowners perspective. However, the overall goal of this initial model is to model a base way of how to principally understand the problem. In chapter 7 a simplified mixed perspective will be approached. The downstream logistics of the supply chain will be included in the model and with this incorporating existing infrastructural aspects for one specific route.

Chapter 6

Initial model

This chapter presents a suggestion to an initial simplified mathematical model to the problem presented in chapter 5. The model will only present the base characteristics and main concept of the defined problem and not all specific challenges related to the system. Specifically, we will only establish a model for the upstream segment of the supply chain. Generating a model to define the optimal location of reception points will be defined in regards to how the different aspects of the problem is considered. The goal is to illustrate the real world problem as best as possible. Modelling a base way of how to principally understand the problem will hence be a good starting point to be able to develop the model.

In the first part of the chapter the model is described, including notation and the mathematical formulation of the model. Further, in Section 6.2, a simple computational study is conducted in order to investigate and evaluate the mathematical model further. Extreme limits of the model and computational case study will be discussed in Section 6.2.2.

6.1 Model description

In order to suitably construct the simple base structure of this problem and model without any influence from the cargo supply chain, the capacity, supply and demand of the vessel and ports are not included in the model. The cost and structure of the system will only be influenced by components related to the CO_2 supply chain.

In the first stage of model development we consider the problem objective, location of CO_2 reception point (RP), as a balance between the investment and operation cost of each RP established (C_i^{RP}), and the lost opportunity cost of reduced cargo capacity of the vessel (C^{LOC}) due to space requirements for the captured carbon. The cost component related to carbon capture will be defined based on the longest distance the vessel will travel, as it is this distance that defines the size of the CO_2 tank needed onboard. A long sailing distance will require a large CO_2 storage tank, and hence less cargo space. A decrease in cargo capacity has a negative affect on the economic profitability of the vessel, that can be interpreted as an additional cost to the system. The proportional increase in this cost is cut when the possibility to unload the CO_2 tanks arise, in other words when a reception point is visited. The tank capacity and related cost is in other words viewed as a linear expression of the distance sailed since last reception point and not a fixed size. The cost contribution from the reception points is a specified fixed cost that is added for each reception point in the system that is visited. This fixed cost is generated from the establishment and operation of the reception points.

For this initial model we are only considering one vessel. We further assume that the vessel sails between a set of ports (P). A start node, s, and an end node, e, are identified as two ports the vessel has to visit. The remaining ports are optional to visit and will only be utilized as possible reception points to unload stored CO_2 onboard the vessel. A reception point is established in each node the vessel visits and it will here unload it's captured CO_2. The ports are further located in a straight line so that there is no faster route than to pass the optional ports.

6.1.1 Model notation

The following notation has been used to describe the problem. P is the set of ports indexed by i and j while A is the set of possible arcs between i and j, restricted by two notations indicating that i has to be lower than j and j can not be equal to zero. The distance between each port is defined through the distance matrix, d_{ij}, that represents the distance of sailing between i and j. A maximum distance parameter, d_{max}, is also introduced to limit the distance the vessel can sail without unloading the captured CO_2. C_i^{RP} is the cost of establishing a reception point for CO_2 in port i while C^{LOC} represents the lost opportunity cost due to CO_2 storage onboard per unit distance the vessel has sailed.

The model aims to provide in which ports the vessel has to unload it's captured CO_2 in order to minimize the total cost of the system. The decision variables that are determined through solving the model have been defined as follows:

- The binary variable y_{ij} gets value 1 if the vessel sails between port i and port j. Otherwise the variable gets the value 0. y_{ij} is further a model technical variable and is not included in the objective function
- The binary decision variable x_i gets value 1 if a reception point is established in port i. Otherwise the variable gets the value 0.

- k^{CO_2} is an auxiliary decision variable that captures the distance of the largest arc (i, j) traveled by the vessel.

Sets:

P : Set of ports, indexed by i and j

A : Set of possible arcs between i and j while $i < j$ and $j \neq 0$

Parameters:

$d_{i,j}$:	Distance of sailing between i and j
d_{max} :	Maximum possible sailing distance between i and j
C_i^{RP} :	Cost of establishing reception point, RP, in i
C^{LOC} :	Cost of sailing per unit distance (lost opportunity cost)

Decision variables:

$$x_i = \begin{cases} 1 & \text{if RP is esablished in i} \\ 0 & \text{otherwise} \end{cases}$$

k^{CO_2} : distance of the longest arc (i, j) traveled by the vessel

Additional variables:

$$y_{i,j} = \begin{cases} 1 & \text{if vessel sails between i and j} \\ 0 & \text{otherwise} \end{cases}$$

6.1.2 Mathematical formulation

In this section, the mathematical formulation of the initial problem is presented. By using the notation introduced in the previous section, the problem can be formulated using the following model.

Objective function:

$$\min z = \sum_{i \in P} C_i^{RP} \cdot x_i + C^{LOC} \cdot k^{CO_2} \tag{6.1}$$

Subject to:

$$\sum_{j \in P} y_{sj} = 1 \tag{6.2}$$

$$\sum_{i \in P} y_{ie} = 1 \tag{6.3}$$

$$y_{ij} \leq x_i \qquad \forall \{i,j\} \in A \tag{6.4}$$

$$y_{ij} \leq x_j \qquad \forall \{i,j\} \in A \tag{6.5}$$

$$\sum_{i \in P} y_{ij} - \sum_{i \in P} y_{ji} = 0, \qquad \forall \{i,j\} \in A \setminus \{s,e\} \tag{6.6}$$

$$d_{ij} \leq d_{max} \qquad \forall \{i,j\} \in A \tag{6.7}$$

$$y_{ij} \cdot d_{ij} \leq k^{CO_2} \qquad \forall \{i,j\} \in A \tag{6.8}$$

$$y_{ij} \in \{0,1\} \qquad \forall \{i,j\} \in A \tag{6.9}$$

$$x_i \in \{0,1\} \qquad \forall\, i \in P \tag{6.10}$$

$$k^{CO_2} \geq 0 \tag{6.11}$$

The objective function (6.1) minimizes the simplified system's total cost according to the relation described in Section 6.1. The function is defined for a homogeneous fleet of vessels. The vessel has to begin its trip in a start node and finish in an end node, this is ensured with restriction (6.2) and (6.3). Further restriction (6.4) and (6.5) ensure that if an arc is traveled, or in other words a port is visited, a reception point has to be established in both of the nodes connecting the arc. Flow conservation between the nodes that are not an element of the start or end node is established by restriction (6.6). Constraint (6.7) makes sure that the distance between two visited ports does not exceed d_{max}.

As we only want the longest distance between two nodes to be the foundation for the lost opportunity cost of the vessel, the model firstly has to identify this maximum value. However, the maximum over all distances multiplied with the respective y_{ij} variables cannot not directly be inserted into the objective function. The introduced auxiliary variable is in the formulation used to reformulate this specific max function and is directly used in the objective function. Constraint (6.7) captures this maximum distance and is further utilized in the objective function to calculate the total lost opportunity cost. Constraint (6.8) and (6.9) impose the variables to binarity while (6.10) imposes non-negativity and integrality to the auxiliary variable.

6.2 Simple computational case study

In order to investigate and verify the mathematical model a simple case example is created. It should be noted that the performed study gives a strongly simplified representation of the problem described in chapter 5. The model and case is implemented into Gurobi Optimization by using python as programming language. For the case example we have chosen a set of five ports where the distances between the ports are given in the distance matrix in Table 6.1. As the system is linear a triangular distance matrix is obtained. The case is illustratively presented in Figure 6.1 with respective distance values.

Figure 6.1: Simple case study

	Port 1	**Port 2**	**Port 3**	**Port 4**	**Port 5**
Port 1	-	50	70	110	170
Port 2	50	-	30	70	130
Port 3	70	30	-	40	10
Port 4	110	70	40	-	60
Port 5	170	130	100	60	-

Table 6.1: Distance matrix, d_{ij}

The vessel has a transportation lap that goes from port 1 to port 5. The vessel hence has to start its journey in port 1 and finish in port 5, indicated by the bright blue frames, reception points are consequently instantly generated in these ports. Further, the vessel has a possibility to stop along its route in predefined ports in order to unload captured CO_2 (port 2, 3 and 4). The cost of establishing a reception point in each port, C_i^{RP}, is given in Table 6.2. Lastly, the two remaining parameters in the model are given in Table 6.3. d_{max} is set so that the vessel can not travel directly form port 1 to port 5.

Port	**Value**
Port 1	10000
Port 2	9000
Port 3	14000
Port 4	20000
Port 5	7000

Table 6.2: Cost of establishing reception point in port, C_i^{RP}

Parameter	**Value**
C^{LOC}	160
d_{max}	140

Table 6.3: Parameter values, case study

The values given for d_{ij}, C_i^{RP}, C^{LOC} and d_{max} are arbitrary, but adjusted so that the cost balance is close to the point of intersection between the two possible actions; stopping in a port and establishing a reception point, or sailing further and generating cost from this.

6.2.1 Results from computational case study

The results obtained from the implemented Gurobi model are presented in Table 6.4. Two solutions are found, where the optimal solution has an objective value of 46 800,- whereby the vessel only visits port 2 between the start and end port. The binary variables that have obtained the value 1 are hence, y_{12}, y_{25}, x_1, x_2 and x_5. The auxiliary variable has obtained the value of 120 which represents the longest distance the vessel has traveled. The vessel's path is illustrated in Figure 6.2

Solution count	2
Optimal solution	Port 1 - Port 2 - Port 5
Objective value	46 800,-

Table 6.4: Result, simple case example

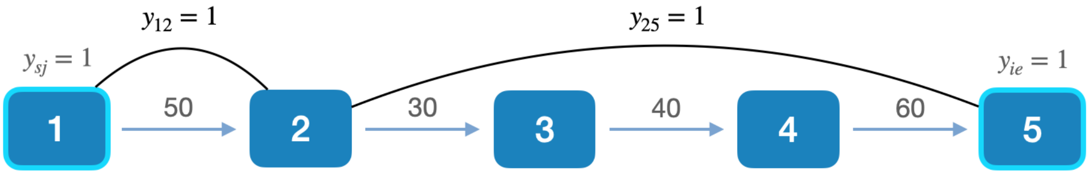


Figure 6.2: Illustrative result, simple case example

6.2.2 Extreme limits of model

Investigating extreme limits of optimization models is beneficial as it often identifies trends and structures in the model. Since generating a fitting base structure is the intention of the initial model, it is interesting to discuss how the model reacts to extreme values. Firstly, we will look at how the lost opportunity cost term in the objective function, $(C^{LOC} \cdot k^{CO_2})$, affects the system.

As explained in Section 6.1, the addressed cost term is for this model definition and interpretation of the problem, a term that increases in proportion to the sailing distance, and hence dependent on the maximum distance variable k^{CO_2}, obtained when solving the model. This is illustrated in Figure 6.3 where the cost is plotted against the distance sailed for an arbitrary slope value and an assumed equal distance between the five ports.

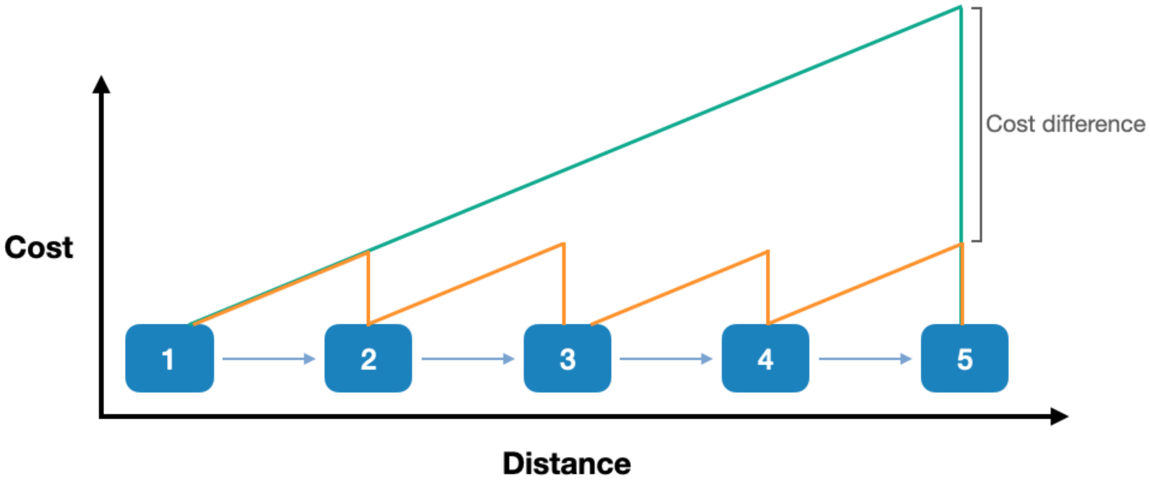


Figure 6.3: Lost opportunity cost, extreme limits

Figure 6.3 presents two generated paths, orange and green, that each illustrate an extreme scenario for the mentioned cost term. The highest peak for the chosen path will determine the term cost, as the term in the objective function is not given as a summation but decided through the maximum distance variable, k^{CO_2}. The orange path is the minimum cost route where the vessel visits each reception point, unloads CO_2 and hence achieves the lowest possible lost opportunity cost for the vessel. The green path on the other hand is the maximum cost route for the addressed term. The vessel travels directly from port 1 to port 5 with the cost increasing proportionally between the two cost.

Further, it is relevant to discuss how the other term in the objective function, the total cost of reception points $\sum_{i \in P} C_i^{RP} \cdot x_i$, influences the described pattern. When a port is visited a reception point is generated and the associated cost is incurred. The value of the reception point will hence determine the optimal outcome amongst the two paths. If the total cost for all reception points is lower than the indicated cost difference in Figure 6.3, the orange path will indicate the optimal solution. However, if this total cost is greater than the indicated cost difference, the green path will be the optimal solution. This further verifies the aim of the initial model development, to generate a model that balances the investment and operation cost of each RP established (C_i^{RP}), and the lost opportunity cost of reduced cargo capacity of the vessel (C^{LOC}) due to space requirements for the captured carbon.

The trends addressed in this section for the different objective function terms are further validated by the developed Gurobi optimization python model. By letting the parameter in the lost opportunity term of the objective function, C^{LOC}, obtain an extremely high value, all the reception points are chosen for the optimal solution, as this minimizes the maximum distance variable k^{CO_2}, and further the lost opportunity cost. Reducing C^{LOC} parameter to a minimum will on the other hand make it more beneficial to travel a longer distance before unloading the CO_2. The model is however restricted and the vessel cannot travel directly from port 1 to port 5, and one additional port is hence visited compared to the theoretical graph in Figure 6.3. The results are presented in Table 6.5.

Cost of sailing per unit distance, C^{LOC}	**Optimal solution**
$160 \cdot 10^{+5}$	Port 1 - Port 2 - Port 3 - Port 4 - Port 5
$160 \cdot 10^{-5}$	Port 1 - Port 4 - Port 5

Table 6.5: Extreme results, illustrative case study

Chapter 7

Extended model

The initial model formulation presented in Section 6.1 can be seen as a relatively simplified representation of the problem described in chapter 5 and mainly include the upstream logistics of the CO_2 supply chain. Several of the activities in the supply chain are not included in the model. The real-life total system would additionally include certain aspects that are less visible from a broad point of view. This is emphasised as the CO_2 supply chain for this problem is underdeveloped. In this chapter extensions to the initial model in chapter 6 are presented and discussed. Further, the extensions are combined with the initial model to a combined deterministic optimization model.

7.1 Model extensions

The simplifications made in Section 6.1 limit the obtained result and model. They are however a good indication of how the base model and important factors of the supply chain function. However, some of the limitations can be eliminated in an extended model formulation by supplementing the model with additional notation and constraints. The following chapter elaborates on two main model extensions that are implemented to handle the limitations of the initial problem formulation. The two extensions can be introduced without changing the main structure of the model and are listed below:

- CO_2 emission taxes for vessels
- Facility location problem for downstream logistics

7.1.1 CO2 emission taxes for vessels

As discussed in Section 3.3, the International Chamber of Shipping (ICS) has recently proposed a global tax on CO_2 emissions from ships as the shipping industry is not covered by the obligations to reduce emissions in the Paris Agreement [26]. This further adds a new element to our problem definition. Not capturing the CO_2 emitted by a vessel will, if the global tax is implemented, induce an additional cost in the supply chain. It will hence be necessary to consider if it is economically beneficial to emit CO_2 and take the shortest route to the end destination, and with this pay CO_2 taxes for the entire trip, or if it serves to visit a reception point, unload the captured CO_2 and pay less or nothing in taxes. The CO_2 emissions must further be priced at a level that provides real incentives to implement technology and infrastructure for such solutions.

By implementing this economical aspect to the model it makes it more sensible to investigate the degree of application for this system as a whole. It will further make it possible to evaluate the economical feasibility of the supply chain in a broad but simple context. It has to be economically beneficial to capture CO_2 if this solution is to be viable. The manner this extension of the problem is included in the model will be further described in Section 7.2.

7.1.2 Facility location problem for downstream logistics

In Section 5.1, a proposed supply chain for shipboard carbon capture is presented. In the initial model from chapter 6, the model was only generated in regards to the upstream segment of the supply chain. It would however be beneficial to evaluate the entire supply chain, including the downstream logistics to the market. The two different segments are presented in the supply chain illustration in Figure 7.1.

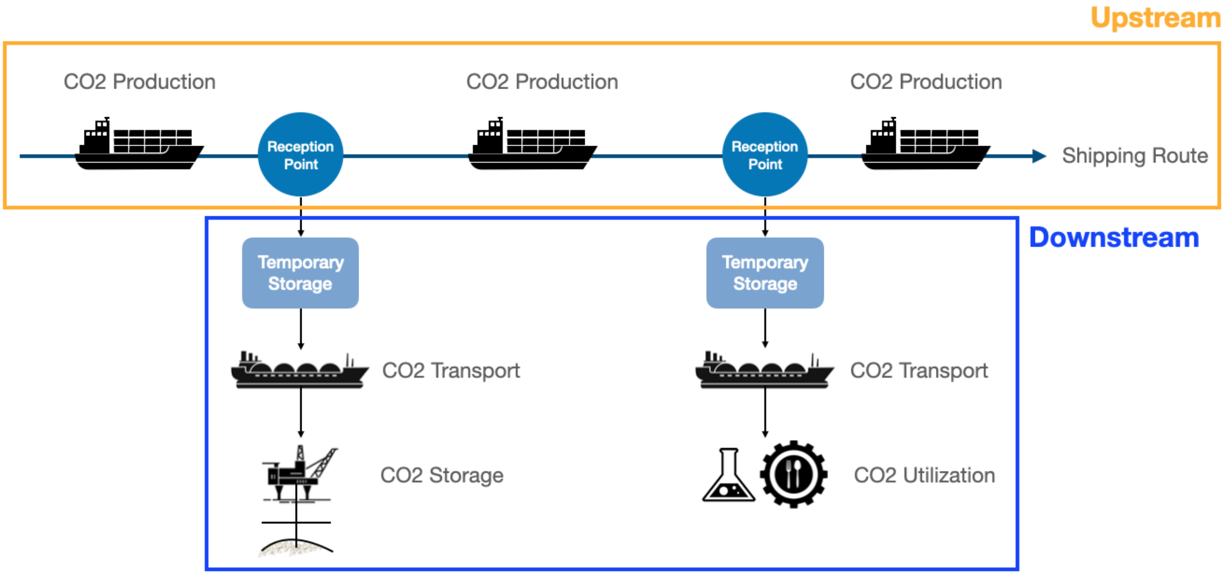


Figure 7.1: Upstream and downstream segments of supply chain

The downstream segment of the supply chain is, as described in Section 5.1, divided into two different branches. One that leads to CO_2 storage and one that leads to utilization of the captured CO_2. In order to simplify the description of further model development these two branches will together be defined as facilities. The discussed facilities can either be considered as storage locations for the CO_2 or facilities that are able to utilize the CO_2. By defining the reception points as supply bases for the facilities the downstream segment of the supply chain can be modeled as a facility location problem. The facilities will act as costumers and the reception points will work as supply facilities in the single-echelon facility location problem presented in chapter 4. By implementing this extension into our initial model, the optimal location of reception points will be based on both the upstream and downstream segment, taking the entire supply chain into account.

7.2 Combined deterministic model

In the following chapter a combined deterministic model for the problem described in chapter 5 is presented. By combining extensions addressed in chapter 7 a more complex and realistic model is obtained. The model is further applied to a generated case study to be able to investigate how the different parameters affect the entire system. A description and relevant assumptions are presented before the model is formulated mathematically.

7.2.1 Model description

For the combined deterministic model, the downstream logistics of the CO_2 supply chain and the implementation of a CO_2-tax cost element are added as extensions to the model presented in chapter 6. Some modifications have hence been made to the initial model.

Instead of letting the model define the largest distance the vessel sails, and with this restricting the maximum sailing distance and size of the CO_2 storage tank onboard the vessel through a decision variable, a distance capacity is set as a parameter for the vessel. This capacitated distance is related to the capacity of the CO_2 tank onboard the vessel. By implementing this as a parameter instead of a decision variable it is possible to add a cost component that generates a CO_2-tax based on the distance traveled that is longer than the set capacitated distance for a specific vessel. This capacitated distance is further, as the decision variable from the initial model, utilized to generate the lost opportunity cost from reduced cargo space for the vessel due to the implementation of a CO_2 storage tank.

Further, the downstream logistics of the supply chain for CO_2 is also implemented in the combined model. For this, facility location theory as presented in chapter 4 is utilized; specifically the single-echelon problem definition. The reception points work as production facilities where the amount of supply is defined by the total amount of CO_2 that is captured by a vessel between two nodes and delivered to that specific reception point. A set of facilities with specific demands are generated and will work as costumers.

In order to suitably construct the simple base structure of this problem and model without any influence from the cargo supply chain, the capacity, supply and demand of the vessel and ports is not included in the model. The cost and structure of the system will only be influenced by components related to the CO_2 supply chain.

Model notation

The notation of the model is in the following section presented. The model includes sets, parameters, decision variables and an additional variable. The notations are in this overview briefly described and will be further elaborated in the model formulation.

Sets:

P : Set of ports, indexed by i
A : Set of possible arcs between i and j while $i < j$ and $j \neq 0$
V : Set of vessels capturing CO_2, indexed by v
F : Set of facilities, indexed by f

Parameters:

d_{ij} : Distance of sailing between port i and j, $[nm]$
d^{max} : Maximum possible sailing distance between port i and j, $[nm]$
d_v^k : Capacitated distance based on CO_2 tank size for vessel v, $[nm]$
C^{TAX} : Tax cost based on ton CO_2 emitted, $[NOK/t\ CO_2]$
C^{LOC} : Lost opportunity cost due to CO_2 tank on vessel $[NOK/t\ CO_2]$
C_i^{RP} : Cost of establishing reception point, RP, in i, $[NOK]$
C_{if} : Transportation cost between RP, i, and facility f, $[NOK/t\ CO_2]$
K_i : Capacity of RP i, $[t\ CO_2]$
D_f : Demand of facility f, $[t\ CO_2]$
B^{CO_2} : Conversion parameter from distance sailed to ton CO_2, $[t\ CO_2/nm]$

Decision variables:

$$x_i = \begin{cases} 1 & \text{if RP is esablished in i} \\ 0 & \text{otherwise} \end{cases}$$

w_v : distance sailed that has exceeded d^k for vessel v
q_{if} : number of tons CO_2 transported from RP i to facility f

Additional variables:

$$y_{ijv} = \begin{cases} 1 & \text{if vessel v sails between port i and port j} \\ 0 & \text{otherwise} \end{cases}$$

p_{ijv} : number of tons CO_2 captured between node i and j for vessel v

Mathematical formulation

In this section, the mathematical formulation of the combined deterministic model is presented. By using the notation introduced in the previous section, the problem can be formulated with the following model. The objective function and constraints are presented before they are thoroughly described.

Objective function:

$$\min z = \sum_{i \in P} C_i^{RP} \cdot x_i \tag{7.1}$$

$$+ \sum_{v \in V} C^{LOC} \cdot d_v^k \cdot B^{CO_2} \tag{7.1a}$$

$$+ \sum_{v \in V} C^{TAX} \cdot w_v \cdot B^{CO_2} \tag{7.1b}$$

$$+ \sum_{i \in P} \sum_{u \in U} C_{iu} \cdot q_{iu} \tag{7.1c}$$

Subject to:

$$\sum_{j \in P} y_{sjv} = 1 \qquad \forall\ s \in P,\ v \in V \tag{7.2}$$

$$\sum_{i \in P} y_{iev} = 1 \qquad \forall\ e \in P,\ v \in V \tag{7.3}$$

$$y_{ij} \leq x_i \qquad \forall\ \{i, j\} \in A \tag{7.4}$$

$$y_{ij} \leq x_j \qquad \forall\ \{i, j\} \in A \tag{7.5}$$

$$\sum_{i \in P} y_{ijv} - \sum_{i \in P} y_{jiv} = 0 \qquad \forall\ \{i, j\} \in A \setminus \{s, e\},\ v \in V \tag{7.6}$$

$$d_{ij} \leq d^{max} \qquad \forall\ \{i, j\} \in A \tag{7.7}$$

$$\sum_{\substack{(i,j) \in A \\ d_{ij} \geq d_v^k}} y_{ijv}(d_{ij} - d_v^k) = w_v \qquad \forall\ \{i, j\} \in A,\ v \in V \tag{7.8}$$

$$\sum_{f \in F} q_{jf} = \sum_{i \in P} p_{ijv} \qquad \forall\ j \in A,\ v \in V \tag{7.9}$$

$$\sum_{f \in F} q_{if} \leq K_i \cdot x_i \qquad \forall\ i \in P \tag{7.10}$$

$$\sum_{i \in P} q_{if} \leq D_u \qquad \forall\, f \in F \tag{7.11}$$

$$d_v^k \geq d_{ij} : \quad p_{ijv} = (d_{ij} \cdot B^{CO_2}) \cdot y_{ijv} \qquad \forall\, \{i,j\} \in A,\ v \in V \tag{7.12}$$

$$d_v^k \leq d_{ij} : \quad p_{ijv} = (d_v^k \cdot B^{CO_2}) \cdot y_{ijv} \qquad \forall\, \{i,j\} \in A,\ v \in V \tag{7.13}$$

The objective function aims to minimize the costs of the entire system. The function is divided into four sub-function. The first term, Equation 7.1, is the cost of establishing reception points in the different ports. Equation (7.1a) is the lost opportunity cost from reduced cargo capacity due to tank storage of CO_2 onboard a specific vessel. Equation (7.1b) is the total cost from CO_2-taxes due to the vessels CO_2 emission after the CO_2 tank capacity onboard the vessel is maximized. Equation (7.1c) is the cost of transporting CO_2 from reception points to the different utility facilities.

Constraints (7.2) - (7.7) are highly similar to the constraints developed for the initial model in chapter 6. However, for the combined model, a set of vessels is included. The binary variable y_{ij} from the previous model, obtains the value 1 if the vessel sails between port i and port j, but for this model the variable becomes y_{ijv}, which influences some of the initial constraints.

Constraint (7.8) captures the distance where the vessel will emit CO_2 due to a sailing distance longer then the capacitated distance, d_v^k, for the vessel. This will influence the CO_2-tax that has to be paid. The number of tons CO_2 transported to facilities has to be less or equal to the amount of CO_2 captured by the vessel between two nodes. This is ensured by constraint (7.9). Capacity constraint (7.10) ensures that the transported quantity of CO_2 to a facility does not exceed the supply from the reception point. Constraint (7.11) establishes that every facility, u, does not receive more then its given demand. Lastly, equation (7.12) and (7.13) assign the CO_2 captured between nodes for each vessel to the variable p_{ijv}.

Chapter 8

Case study using combined deterministic model

For the initial model presented in chapter 6, an illustrative case was conducted in order to validate and better understand the basic structure and principles of the model. However, for the combined deterministic model from Section 7.2, including the discussed model extensions, it will be beneficial to connect the model to real-world values and with this create a more realistic case.

The Gurobi model developed for the initial model in chapter 6 is extended to include the extensions presented in chapter 7. Values for the specific case study presented in the following chapter are read in from an excel file. The generated spreadsheets are appended in Appendix A.

In this chapter the combined deterministic model will be used to find optimal locations of reception points for a simple roundtrip in the North Sea based on vessel parameters and operation and further distribution of the captured CO_2 to end-costumer.

8.1 Case description

A North Sea based case is generated, the route is illustrated in Figure 8.1. The case considers a vessel that sails from Rotterdam (RTM), to Gothenburg (GOT), to Bergen (BGO) and with its final stop in Aberdeen (ABD). This route is mainly chosen based on the fact that information about ports and connecting infrastructure is easier retrieved and available. Also it gives the opportunity to connect the route to existing infrastructure in the North Sea, and consider the effects of this. As the route includes four ports that have to be visited, the optimization model is modified to force flow through these nodes.

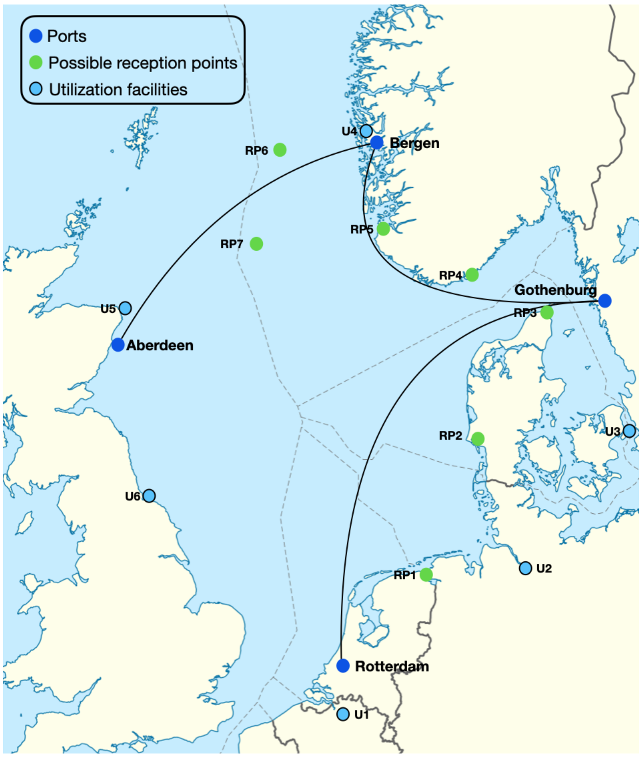


Figure 8.1: Case overview, North sea

A set of reception points is predefined between each port on the route. Most of these are placed in existing ports that are somewhere along the vessel's route. It is initially assumed to be no established CO_2 infrastructure in the port based reception points. Between Bergen and Aberdeen the reception points are placed at offshore oil and gas platforms found through *factpages.npd.no* that contain information regarding petroleum activities on the Norwegian continental shelf. These platforms are assumed to be utilized as existing infrastructure and CO_2 can be directly utilized for enhanced oil recovery or injected for subsurface storage. The ports and offshore platforms are listed in Table 8.1.

Reception point	**Location**
RP1	Eemshaven
RP2	Esbjerg
RP3	Hirsthals
RP4	Kristiansand
RP5	Stavanger
RP6	Platform: OSEBERG SØR
RP7	Platform: GUDRUN

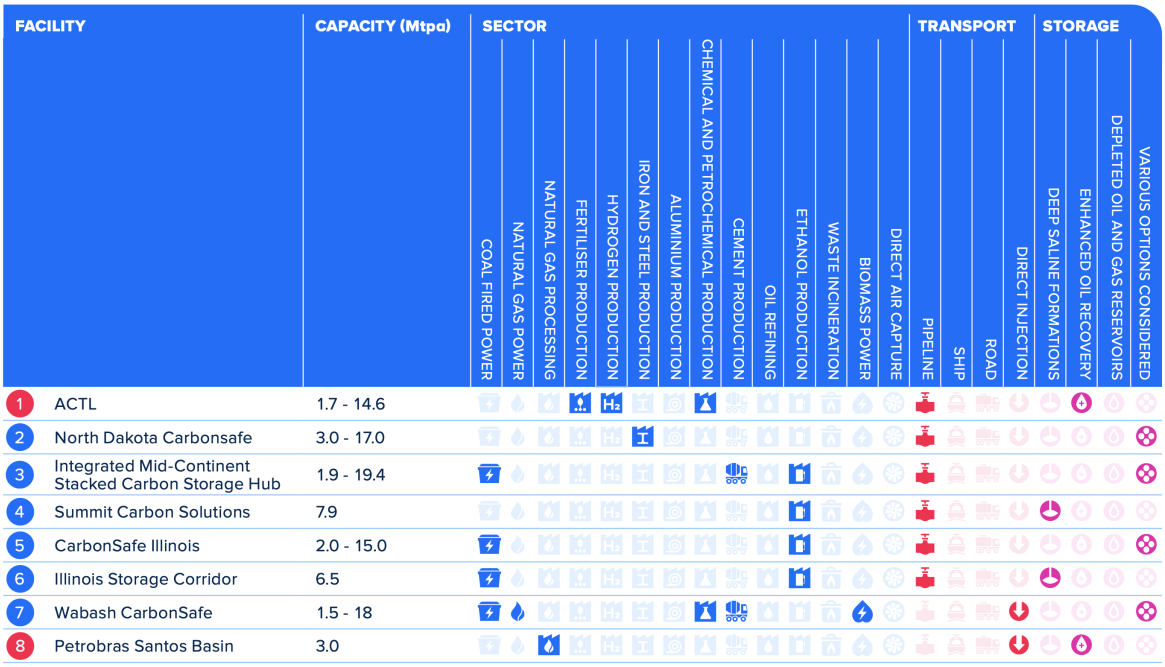
Table 8.1: Reception points specific location

Figure 8.1 further illustrates the facilities the captured CO_2 will be distributed to. The location of these facilities is given in Table 8.2. The two platform reception points, Oseberg Sør and Gudrun, in Table 8.1 could also be included as a facility as this is identified as the end-costumer for captured CO_2, but as we can assume that there is no transportation lap between the unloading and injection of the CO_2 onboard the platform the distribution segment of the supply chain can here be neglected.

Facilities	**Location**
U1	Antwerp@C, Belgium
U2	Farm, Germany
U3	C4 Copenhagen, Denmark
U4	Langskip, Norway
U5	Acorn, United Kingdom
U6	Net Zero Teesside, United Kingdom

Table 8.2: Facilities spesific location

The location of the different facilities in Table 8.2 are based on different CCS networks in the North Sea area indicated by the Global CCS institute's status report for 2021 [10]. Figure 8.2 illustrates the overview given in the same report, indicating facilities, their respective capacity, sector, transport and storage solution. Some of the facilities are production facilities that emit CO_2 and are generating carbon capture and storage solutions to reduce their own emissions, and others are CCS networks established to capture, transport and store CO_2 from a cluster of companies or industries. However, as there is a CCS network connected to these facilities it is for this case study assumed that the different facilities are able to receive CO_2 captured by the vessel in our described route, and that it can be further included in the transport and storage solution of the network, and even down the line contribute to the production of e-fuels for the facilities that produce hydrogen.



FACILITY	CAPACITY (Mtpa)	SECTOR														TRANSPORT				STORAGE			
		COAL FIRED POWER	NATURAL GAS POWER	NATURAL GAS PROCESSING	FERTILISER PRODUCTION	HYDROGEN PRODUCTION	IRON AND STEEL PRODUCTION	ALUMINIUM PRODUCTION	CHEMICAL AND PETROCHEMICAL PRODUCTION	CEMENT PRODUCTION	OIL REFINING	ETHANOL PRODUCTION	WASTE INCINERATION	BIOMASS POWER	DIRECT AIR CAPTURE	PIPELINE	SHIP	ROAD	DIRECT INJECTION	DEEP SALINE FORMATIONS	ENHANCED OIL RECOVERY	DEPLETED OIL AND GAS RESERVOIRS	VARIOUS OPTIONS CONSIDERED
① ACTL	1.7 - 14.6				✓	✓			✓							✓					✓		
② North Dakota Carbonsafe	3.0 - 17.0						✓									✓							✓
③ Integrated Mid-Continent Stacked Carbon Storage Hub	1.9 - 19.4	✓								✓		✓				✓							✓
④ Summit Carbon Solutions	7.9											✓				✓				✓			
⑤ CarbonSafe Illinois	2.0 - 15.0	✓										✓				✓							✓
⑥ Illinois Storage Corridor	6.5	✓										✓				✓				✓			
⑦ Wabash CarbonSafe	1.5 - 18	✓	✓						✓	✓				✓					✓				✓
⑧ Petrobras Santos Basin	3.0			✓															✓		✓		

Figure 8.2: CCS networks around the world, *provided by Global CCS Institute* [10].

Further, the total number of trips the vessel will complete during the span of a year will have to be calculated as it will be relevant for input calculations for the model. If we assume that the vessel keeps an average speed of 18 knots, the route between the four ports without visiting any reception point is calculated to take 2 days and 15 hours. As the vessel most likely will have to visit one or several reception points we assume that the route will take an average of 3 days and further an average of 7 trips per month including necessary repair of the vessel. The route will hence be completed 84 times each year.

8.2 Required input for case study

The optimization model requires several input parameters. Firstly some of the general parameters will be addressed before the distances and cost parameters are presented.

Conversion parameter

The model includes a conversion parameter, B^{CO_2}, to convert the distance sailed by the vessel to ton of CO_2. The parameter will have the unit [ton CO_2/km] in order to convert the distance to ton CO_2. For several different modes of transportation it has been identified how many grams of CO_2 are emitted by transporting 1 ton of cargo 1 km, illustrated in Figure 8.3

Figure 8.3: Grams of CO_2 emitted by transporting 1 ton of cargo 1 km, using respectively container vessels, trains, trucks or planes, *provided by Brouer B. et al.* [35].

This can be used to calculate the conversion parameter if the number of tons transported is known. We will for this case only be looking at one 1000 TEU container vessel and can assume that this vessel will have a capacity of around 10 000 ton. Although Figure 8.3 indicates that the value applies to Triple-E container vessel, the same value is assumed for a 1000 TEU vessel. With this data we can calculate the conversion parameter for the specific vessel.

$$B^{CO_2} = \frac{3\ [gCO_2/tkm] \cdot 10000\ [ton]}{1000\ [g]} = 30\ [kgCO_2/km] = 0,03\ [tonCO_2/km] \tag{8.1}$$

Reception point capacities

Further the reception points CO_2 capacities for temporary storage before further distribution has to be identified. The maximum distance between two ports is set to 1000 km. The reception points hence have to have the capacity to store the amount of CO_2 captured over this distance. Using the conversion parameter B^{CO_2} the reception point has to be able to store a minimum of 30 tons CO_2. It can be relevant to include a security factor for the capacity in the different ports. For the larger ports where the vessel is set to visit and unload both cargo and its captured carbon (ROT, GOT, BGO and ABD) the calculated capacity is multiplied by 6. Further in the smaller ports that are exclusively reception points the calculated capacity is multiplied by 4. For the reception points place on offshore platforms the capacity is set a lot higher as the capacity of the reception point is based on the storage capacity under the seabed. The capacity here is set to 300 tons. If several vessels were to be included in the model the capacity in the reception points would have to be increased and multiplied with the number of vessels visiting the specific ports.

Reception point	**Capacity [ton CO_2]**
Rotterdam	180
Eemshaven	120
Esbjerg	120
Hirsthals	120
Gothenburg	180
Kristiansand	120
Stavanger	120
Bergen	180
Platform: OSEBERG SØR	300
Platform: GUDRUN	300
Aberdeen	180

Table 8.3: Reception points capacity

Facility demand

The distribution of CO_2 from the different reception points to end-costumer is mainly based on the transportation cost between the reception points and facilities. However, the facilities have certain capacities that can not be exceeded. In the model this is referred to as demand as it is based on the facility location problem. This demand or amount of CO_2 that can be transported to the different facilities has to be identified. Figure 8.2 presented in the case description indicates the capacity of the networks chosen as facilities. The capacities are given in million tons per annum and are for some facilities given as a range of capacity. The lowest value is here chosen. The values are given for the captured CO_2 in the entire established network. Hence, we assume that our system can demand 1% of the total capacity of specific facilities. Further, in order to apply these values as the demand for each trip, the values have to be divided by the number of trips completed by the vessel in one year, 84, as the values are given in per annum. For the farm in Germany we assume a demand of 5 tons of CO_2. The resulting ”demand” for each facility is given in Table 8.4.

Facility	**Demand [ton]**
Antwerp@C, Belgium	1070
Farm, Germany	10
C4 Copenhagen, Denmark	360
Langskip, Norway	180
Acorn, United Kingdom	600
Net Zero Teesside, United Kingdom	100

Table 8.4: Capacity at facilities

8.2.1 Distances

The distances between all ports and reception points in the system have to be identified and added to a distance matrix as input to the model, given as the parameter d_ij. The distances are found by using *classic.searoutes.com* that calculates nautical miles between ports. The calculated distances are converted to km and added to Table 8.5.

	RTM	RP1	RP2	RP3	**GOT**	RP4	RP5	**BGO**	RP6	RP7	**ABD**
RTM	0	343	541	767	902	750	815	983	980	822	761
RP1		0	372	617	707	619	728	907	924	750	785
RP2			0	324	446	326	456	635	669	557	682
RP3				0	126	131	344	526	576	519	726
GOT					0	244	457	639	687	632	846
RP4						0	230	411	457	402	615
RP5							0	269	296	311	554
BGO								0	185	306	567
RP6									0	194	435
RP7										0	259
ABD											0

Table 8.5: Distance matrix, [km]

The capacitated distance parameter in the model is initially set to a middle value of 600 km based on the calculated values in the distance matrix. This parameter will at a later stage be adjusted and utilized for a parameter study in order to investigate possible outcomes and results of the model.

8.2.2 Estimating cost parameters

The combined deterministic model further includes several cost parameters. These parameters will in the following section be calculated and assumed as best as possible with available data.

Cost of establishing reception point

Firstly the cost of establishing the reception points has to be determined. As infrastructure for shipboard carbon capture is not a developed system, this cost will be hard to estimate and simplification and assumptions will have to be made. In the reception points there has to be established systems to unload and store the CO_2. As we are considering a container vessel, we assume that the technology presented by Value Maritime [25], using container sized modules as CO_2 tanks onboard the vessel that can be unloaded in the same manner as the containers, will be utilized. This simplifies the unloading of the CO_2 to only include the use of a crane and truck. Further, an area in the ports has to be established to temporary store the captured CO_2.

As the model is only considering the CO_2 supply chain and not any aspects of the cargo supply chain, costs related to the general operation of the vessel is not included. Generally port dues are for instance an important cost parameter in most routing problems related to shipping, and they are initially not included in this model. In the main ports where cargo handling also would occur the port dues would be included in the general routing problem considering the cargo distribution. However, in the ports that are only visited in order to unload CO_2 these costs will also occur, but this would not be included in the routing problem. Due to this we can assume that the cost of establishing reception points in these smaller ports will be somewhat higher as the port dues also have to be considered in the system under consideration. Additionally it is assumed that establishing new infrastructure is higher in smaller ports.

There are three different types of reception points addressed in this case problem:

- Cargo handling ports
- Smaller ports, only reception point
- Offshore platforms

For simplicity we assume that the smaller ports is the base case for the establishment cost. The cost of establishment in cargo handling ports is as described assumed to be lower and will be taken as 80% of the base case. Establishing new infrastructure offshore is generally expensive. For this specific case it is assumed that the infrastructural aspects will be simple and connected to already existing infrastructure on the platform; it will however be taken as 120% of the base case. The assumed cost for establishing reception points in the smaller ports is set to 500 000 \$. With an interest rate of 5% and 10 annuities the capital recovery factor is:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} = 0,13 \tag{8.2}$$

This further indicates a payment of 65 000 \$/year for each reception point. As it is assumed that the vessel will complete 84 trips each year the average establishment cost for each reception point is 775 \$/trip for the base case.

Lost opportunity cost due to CCS

The value a vessel generates for the ship owner is strictly related to the amount of cargo the vessel is able to transport. Capturing the CO_2 that is emitted from combustion of fuel and storing it onboard the vessel will take up some of the value generating space onboard the vessel, especially for container vessels as they are space critical. This cost is referred to as the lost opportunity cost. Firstly the value of one transported TEU has to be established.

UNCTAD (United Nations Conference on Trade and Development) has in their *Review of maritime transport 2021*, [36], published average contract freight rates for a 40-foot container across different continents. The average contract freight rate for a 40-foot container from Europe to Europe is set to be 887 \$. From this an average freight rate of 450 \$ per TEU (20-foot container) can be assumed. One 20-foot container has a volume of 33,2 m^3.

The space the combusted CO_2 occupies will further need to be calculated. 1 kg CO_2 is equal to 0,986 L of liquid CO_2 [37], which further can be simplified to 1 ton CO_2 is equal to 1 m^3 CO_2 as 1000 L = 1 m^3. One container can hence be filled with 33,2 tons of CO_2. The lost opportunity cost for one cargo transportation leg can further be calculated.

$$\frac{450\ [\$/TEU]}{33,2\ [tonCO^2/TEU]} \approx 14\ [\$/tonCO^2] \tag{8.3}$$

As the CO_2 tank space is set as a fixed parameter for each vessel, the lost opportunity cost will have to be included for each leg between cargo unloading ports. For this specific case study we are transporting cargo between four different ports and there will be in total three legs that will be influenced by the lost opportunity cost. The resulting lost opportunity cost becomes:

$$C^{LOC} = 3 \cdot 14\ [\$/tonCO^2] = 42\ [\$/tonCO^2] \tag{8.4}$$

CO2 tax cost

Although UN's CO_2 quota market does not cover the shipping industry the International Chamber of Shipping (ICS) has recently proposed a global tax on CO_2 emissions from ships as mentioned earlier in this thesis, [26]. As these measures are not yet in place the European Union Emissions Trading System will be the foundation of the CO_2 tax cost in this model.

The carbon emission pricing has increased dramatically the last year. In January 2021, Refinitiv Financial Solutions assumed that the carbon emission price will reach 90 euro per ton CO_2 by 2030 [38]. But in February 2022 the carbon emission price almost reached 100 euro per ton CO_2 and is assumed to still increase in the years to come [39]. As it will take some time before the infrastructure related to shipboard CCS is implemented a predicted pricing is more applicable. The CO_2 tax cost is for this case study hence set to 180 \$/ton CO_2.

Transportation cost to facility

Lastly the transportation from reception point to facility has to be determined. Based on the report *Ship transport of* CO_2, [40], the cost of transporting CO_2 is based on the distance traveled by the vessel. Assuming that all the CO_2 captured is distributed to end-costumer by ship, the findings from this report can be utilized to calculate the transportation cost in our system.

The distances between the reception points and facilities are found by using *classic.searoutes.com*. In the report, [40], transportation costs are given for the distances 200, 500, and 1000 km as presented in Table 8.6. The remaining values in the table are obtained by interpolation. As the distances between the reception points and facility vary, the distances are rounded up or down to the nearest value according to Table 8.6 and with this assigned the transportation cost in the right column.

km traveled	\$/tonCO_2
200	12,4
350	13
500	14,6
750	15,5
1000	17

Table 8.6: Defining C_{iu}

8.3 Results, North Sea case study

In the following section the results from the North Sea case study is presented. The parameter values are set based on the aforementioned calculations and assumptions, and solved with the Gurobi solver developed in chapter 7. Figure 8.4 presents the resulting route for the vessel. The CO_2 captured on each transportation leg is indicated in the figure along the respective arc.

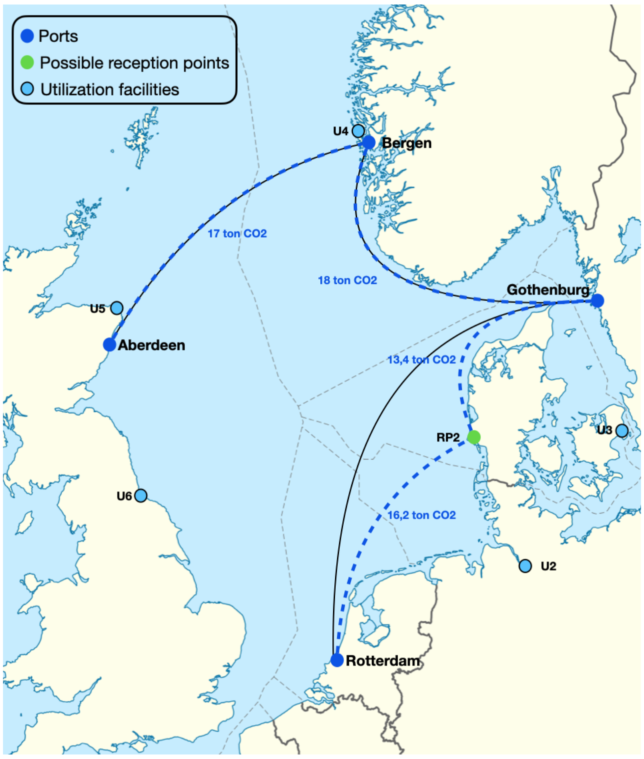


Figure 8.4: Result, vessel route

The generated optimal route for the vessel only visit reception point 2 in addition the the cargo handling ports. The longest distance the vessel sail without unloading CO_2 is 639 km, from Gothenburg to Bergen. This distance is 39 km longer then the vessels capacitated distance, d_v^k, for this specific case. This generates a CO_2 tax cost of 210,6 $ for the entire route. The solver found two solutions to the model. The optimal solution and objective function value is presented in Table 8.7.

Solution count	2
Optimal solution	RTM - RP2 - GOT - BGO - ABD
Optimal function value	5042 $

Table 8.7: Result values, North sea

Figure 8.5 illustrates the distribution and downstream logistics of the captured CO_2 that is unloaded in ports and reception points. The respective CO_2 transported to the facilities is also indicated in the along the respective arcs in the figure. The captured CO_2 is distrubuted to all facilities except for Antwerp@C in Belgium.

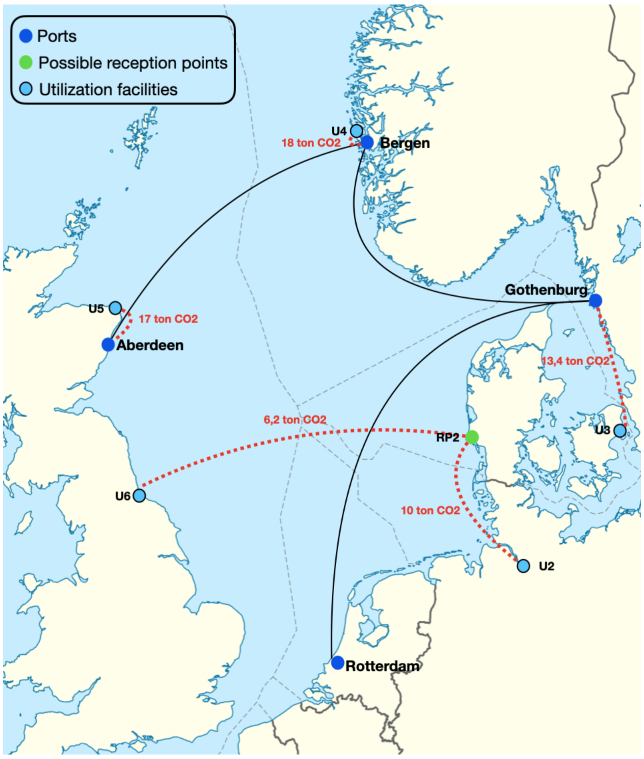


Figure 8.5: Result, downstream logistics

8.3.1 Parameter study

A parameter study is further conducted for the North Sea case. It is valuable to study other possible outcomes of the model as some of the defined values are not truly deterministic and will vary over time or based on vessel specification. The parameter study is done by varying two different parameters, the capacitated distance, d_v^k, and the carbon tax cost, C^{TAX}. The study is conducted for five different different d_v^k values, 200, 400, 600, 800 and 1000 km. As described in chapter 7 the capacitated distance, d_v^k, can be interpreted as the carbon tank size onboard the vessel, as it will, if multiplied by the presented conversion parameter, B^{CO_2}, gain the unit ton CO_2. Ton of CO_2 is assumed to be directly convertible to m^3 of CO_2. For each capacitated distance, three different carbon taxes are explored, 100, 200 and 300 \$/ton CO_2. The obtained results from the parameter study are presented in Table 8.8.

d^k [km]	C^{TAX} [\$/ton CO_2]	Optimal value [\$]	w_v^k [km]	Optimal route
200	100	7478	1508	RTM - GOT - BGO - ABD
	200	11 473	1122	RTM - GOT - 4 - BGO - 7 - ABD
	300	14 197	667	RTM - 2 - 3 - GOT - 4 - 5 - BGO - 6 - 7 - ABD
400	100	6143	593	RTM - 2 - GOT - BGO - ABD
	200	7302	198	RTM - 2 - GOT - 4 - BGO - 7 - ABD
	300	7543	57	RTM - 1 - 2 - GOT - 4 - BGO - 7 - ABD
600	100	4916	341	RTM - GOT - BGO - ABD
	200	5066	39	RTM - 2 - GOT - BGO - ABD
	300	5182	39	RTM - 2 - GOT - BGO - ABD
800	100	4534	102	RTM - GOT - BGO - ABD
	200	4846	102	RTM - GOT - BGO - ABD
	300	5044	0	RTM - 3 - GOT - BGO - ABD
1000	100	4524	0	RTM - GOT - BGO - ABD
	200	4524	0	RTM - GOT - BGO - ABD
	300	4524	0	RTM - GOT - BGO - ABD

Table 8.8: Results, parameter study

The results for optimal routes in Table 8.8 presents reception point 2 and reception point 7, respectively Esbjerg and Gudrun Platform, as the most visited reception points from the parameter study. Hence, it is clear that these reception points will be beneficial to establish based on a broad variation of CO_2 capacity onboard the vessel and an increasing CO_2 tax in the industry.

Further, it is clear that the optimal objective function value of the system decrease with increasing tank size, or capacitated distance, onboard the vessel. The cost further increase with increasing carbon price. An increase in capacitated distance further decrease the significance the carbon price has on the total cost. Additionally, for several of the solutions there are no established reception points, this particularly applies to the results with a C^{tax} of 100 \$/ton CO_2.

Considering the highest carbon price the optimal value is the highest for the lowest tank volume, or d_v^k, as a lot of the carbon will not be captured during the vessels route and the lack of carbon storage onboard increase the number of reception points the vessel visits. For the capacitated distances 600, 800 and 1000 km the differences in optimal value is quite low. This indicates that once the tank size reach a certain size the cost difference stagnates.

The two outer points of results from the parameter study are quite clearly not optimal solutions. For low carbon tank sizes the optimal value increase dramatically with increasing carbon prices and large carbon tanks will take up large areas onboard the vessel. The overall optimal solution will hence lie somewhere in the middle.

8.4 Discussion of results

In the following section the results obtained in Section 8.3.1 will be discussed. The model development and assumptions made will be further discussed in chapter 9.

8.4.1 Routing from parameter study

From the parameter study it was clear that it would be beneficial to establish a reception point in Esbjerg and on the platform Gudrun. However, for most of the routing solutions with a CO_2 tax of 100 \$/ton CO_2 the vessel does not visit any reception point. This validates the importance of implementing carbon taxes and quotas in order to create real incentives to develope sustainable solutions to decarbonize the shipping industry. On the other hand, one could say that this enhance the importance of extending the model and conducting the study with several different routes and vessel types in one specific area, and from this obtain a greater optimal solution.

Implementing the largest CO_2 storage tank onboard the vessel that corresponds to a capacitated distance of 1000 km implies that all of the CO_2 will be stored onboard the vessel and no reception points will be visited. This applies to all three C^{TAX} used and result in the lowest optimal objective function value. A shipowner will nevertheless always strive to carry as much cargo as possible, as this is what generates revenue for the vessel. If the lost opportunity cost of the vessel obtained a higher value in the case, the resulting routes for the high capacitated distance might be more expensive then some of the other solutions.

8.4.2 Comparison with existing solution

The results can also be discussed by comparing the results presented in Section 8.3 with cost values for today's solution. An approach to do this is to compare the obtained results from the model and parameter study, obtaining optimal location of reception points, with the cost of sailing the same route without an implemented carbon capture system. All the combusted CO_2 will then be emitted to the atmosphere and the only cost generated for the system is the C^{TAX} cost for sailing this route. This can be interpreted as one of the terms included in the objective function and can be rewritten as:

$$C^{TAX} \cdot d^{TOT} \cdot B^{CO_2} \tag{8.5}$$

The distance of sailing the entire route without visiting any of the predefined reception points is 2095 km. Table 8.9 presents the total carbon tax cost based on this distance for the same taxes utilized in the parameter study in Section 8.3.1.

C^{TAX} [\$/ton CO_2]	Cost [\$]
100	6285
200	12 570
300	18 855

Table 8.9: Carbon tax cost of total route without carbon unloading

From these calculations it is clear that implementing carbon capture onboard the vessel will pay off for many combinations of capacitated distance and C^{TAX}. The cost of emitting CO_2 is already high in many industries. Implementing CO_2 taxing and quota systems in the shipping industry will increase the push and motivation for ship owners to implement the technology onboard their vessels. The highest pay off by comparing the existing solution with the case study, applies to the largest capacitated distance and carbon tank size, especially as the CO_2 tax increase. For vessels where the tank size does not influence the cargo capacity to the same extent as it does for a container vessel, implementing carbon capture and storage solutions onboard seems beneficial.

This comparison is however not entirely valid, as the cost of retrofitting vessels with carbon capture technologies is not included in the optimization model. The results nevertheless give a good indication of the cost difference between these solutions. If CO_2 taxes are implemented in the industry the ship owner will be forced to invest in emission reducing solutions that all will have an initial establishment cost. These solutions has so far been based on building zero-emission vessels or retrofitting entire propulsion systems. Both of which are high cost solutions and can be assumed to in total have higher investment costs compared to carbon capture technologies due to its high maturity for onshore application. The high maturity will ensure a future decrease in investment costs for the technology.

Chapter 9

Discussion

This chapter includes a discussion of the proposed supply chain and developed mathematical optimization model. Firstly, the infrastructural aspects and approach will be addressed before the general assumptions and simplification made throughout the thesis is discussed. Secondly, there is a discussion of the development of the model.

9.1 Infrastructural problem solving

Carbon capture and storage technologies seem to be accelerating in the shipping industry. Although the technology is developing to become feasible for implementation onboard vessels, the development and focus on relevant infrastructure will also define how implementable the technology becomes. It might even reduce the cost of the total system if designed properly.

In order to establish good infrastructure it is important to fully understand how the vessel operates with the implemented technology and how to best establish infrastructure related to this. Infrastructural systems can be designed in several ways and many aspects needs to be taken into consideration. As discussed in Section 5.2.1 the system can be approached from different perspectives which will influence the resulting design. The system can be designed in different ways depending on how the different aspects are evaluated.

If the goal is to emit the least amount of CO_2 while minimally influencing the vessel's cargo capacity, the optimal solution would be to generate reception points for the captured CO_2 as frequently as possible. This would be attractive for a shipowner as the cargo is the revenue generator. However, it induces a cost by the establishment and investment of the reception points. Who will pay and define the optimal location for these reception point? If each shipowner is to build and locate their own reception points for the operation of their vessels and routes, it will not be beneficial for the infrastructure considered as one unit. This would generate additional costs for all shipowners rather then having a collected amount of reception points utilized by several shipowners. It will hence be beneficial to study the optimal location of these reception points across a diversity of perspectives, parameters and shipping routes. The optimal location of the reception points will depend on the existing infrastructure for CO_2 and carbon capture and storage, and not only vessel operation. The design of downstream logistics will hence also influence the optimal design. How is this infrastructure implemented into the system in a best possible manner? The design of infrastructure offers many questions, and a selection of them are discussed and presented in this thesis.

9.2 Assumptions and simplification

Simplifications and assumptions have been made throughout the thesis. Firstly, it is assumed that carbon capture and storage technologies are implementable as shipboard application. As presented in chapter 3 several companies have begun the process of implementing carbon capture technologies onboard their vessels, some vessels even have the technology currently installed.

The consideration on type of capture technology has been neglected throughout the thesis, in order to exclude this as an aspect of consideration when infrastructural aspects are considered.

An additional assumption which has limited the development of both the infrastructural discussion and model development, is that the thesis has only considered the supply chain of the captured CO_2 to end-costumer. Optimization problems related to the shipping industry normally concerns cost minimization of vessel routing, based on cargo distribution. This is not included in the model or infrastructure development in the thesis, in order to isolate the specific problem and with this simplify the modelling. Due to this it is debatable how realistic the results are as this is the fundamental operation for a vessel and shipowner.

It is however valuable to develop basic structural models of new concepts in order to gain a broad understanding of main principles concerning the addressed infrastructural aspects. Additionally, it is not unlikely that the shipping industry, as for many others, could soon depart from its one-sided focus on cost minimization and profitability, and increasingly integrate their contribution to the environmental cause as a competitive edge. In light of this, it is a valuable course to access aspects that do not touch upon profitability.

9.3 Model development

When developing an optimization model, decisions have to be made on how to interpret the given problem. As discussed earlier in this chapter there are several ways to establish and interpret the infrastructure concerning shipboard carbon capture, and hence, several methods of approaching the optimization of locations for the reception points. Firstly, the model specific parameter, d_v^k, will be discussed in the following.

When extending the initial model and including the downstream logistics and CO_2 tax, the variable k^{CO_2}, the auxiliary decision variable that captures the distance of the largest arc traveled, intentionally changed to a parameter. This was in order to be able to capture the distance traveled without the vessel capturing any CO_2 and hence inducing a CO_2 tax price on the system. However, it would be interesting to consider this as a variable in the extended model as well, as it adds an additional aspect to the system. Modeling the optimal location of reception points not only based on a preset of tank sizes, but obtaining approximated optimal tank size for the infrastructural system.

The model developed in this thesis maps the location of reception points based on a specific route, vessel and capture operation, and a set of predefined reception points. This way of modeling gives the opportunity to include existing infrastructure if the predefined reception points for instance are placed in the same area as CCS facilities or on platforms. However, there are several ways to approach the modeling of this problem. Calculating the total CO_2 emission along different paths and making this one of the deciding factors for finding optimal locations is one of them. Taking a more economical perspective is another, letting the amount of CO_2 emissions or vessel traffic around a specific point decide if it is financially beneficial to establish a reception point.

At later stages the reception points will be considered based on their established location, the vessels will sail and unload CO_2 and the reception points will become a part of the routing optimization for the vessels. Modeling the optimal location of the reception points as best as possible, based on multiple routes and parameters, will hence lay the foundation of how the infrastructure is established and further routing optimization for vessels with a carbon capture solution implemented onboard. The optimization model developed in this thesis can hence not be utilized for routing purposes once the infrastructure is established, but is a model for establishing good infrastructure. This further shows the importance of laying a good foundation in the development of infrastructure for new technologies within the transportation sector.

Lastly, it is worth mentioning that the type of model developed in the thesis can be fitted to different types of problems and technologies presented in the shipping industry today. Generating a general approach of understanding and solving infrastructural problems similar to this will be beneficial for the entire industry and development of new zero-emission technologies. Similar problems could be locating energy hubs for deep-sea shipping, or charging stations for electrical driven vessels. Both these problems will be dependent on some of the same factors and should be built up by considering several routes and vessel specification, as "fuel range", in order to find the optimal solution. In a broad view the different infrastructural problems can further be combined. The energy hubs, charging stations and CO_2 reception points could be merged and located in the same location, and a joint overall model considering optimal location for several technologies could be implemented.

9.4 Further work

The discussions presented throughout this chapter are finalized with a set of proposals to further research, development, extensions, and approaches to the model formulations presented. The section provides suggestions on how the work can be continued and presents aspects interesting to study further.

- The predefined reception points and ports should in the model be defined by coordinates instead of only distance matrices. This would make the model easier to modify to fit new areas and vessel routing with generating the distance matrix itself based on coordinates. It would additionally make it easier to generate visual plots of the generated routes.
- In relation to the previous point, there could further be developed a database consisting of coordinates for possible reception point based on exciting infrastructure. The database could either be based on specific routes or general areas and also include an establishment cost for the specific type of reception point. This would additionally require further research on possible reception points.
- The layout of the reception points with different and optimal ways of unloading the carbon has to be studied in order to minimize cost and time spent in the reception point.
- In the previous section, different ways to model the optimal location of reception points are discussed. However, it could be valuable to consider how to model the optimal location of the reception points as a part of the vessel routing problem for several types of vessels and routes, as this most likely will give a more accurate result the a specific route.

Chapter 10

Conclusion

This thesis aimed to propose and develop logistical aspects needed for carbon capture to be an attractive and implementable technology in decarbonizing the shipping industry. A supply chain for the shipboard captured CO_2 was developed while incorporating existing infrastructural aspects. Further, an optimization model that generates optimal location of reception points for shipboard carbon capture based on the proposed supply chain was created.

Two different optimization models were developed. The initial model was created to gain a base way to principally understand the problem. The model was extended to include downstream logistics including existing infrastructure and a CO_2 emission tax. The developed extended optimization model was successfully tested in case study based on a route between four ports in the North Sea: Rotterdam, Gothenburg, Bergen and Aberdeen. The conduction of a parameter study utilizing the extended model made it possible to find optimal location of reception points based on several input parameters. Based on the parameter study for the specific route, two reception points, Esbjerg and the Gudrun platform, were found to be the most optimal to establish. Additionally the model development gave insight into the importance of establishing valuable infrastructure for new zero-emission technologies within the shipping industry.

Fossil fuels are still considered the most efficient fuel in the shipping industry, both related to price and energy efficiency. However, we are well on our way in developing alternative fuels and zero-emission solutions, for instance with the use of green corridors. As the majority of the world fleet still consist of conventional vessels, we need to be able to find good sustainable solutions for using fossil fuels in years to come. This has to be done in ways that do not emit CO_2. In the process of transitioning from fossil-based to zero-emission fuels, shipboard carbon capture will be an important contribution in reducing the shipping industry's carbon footprint.

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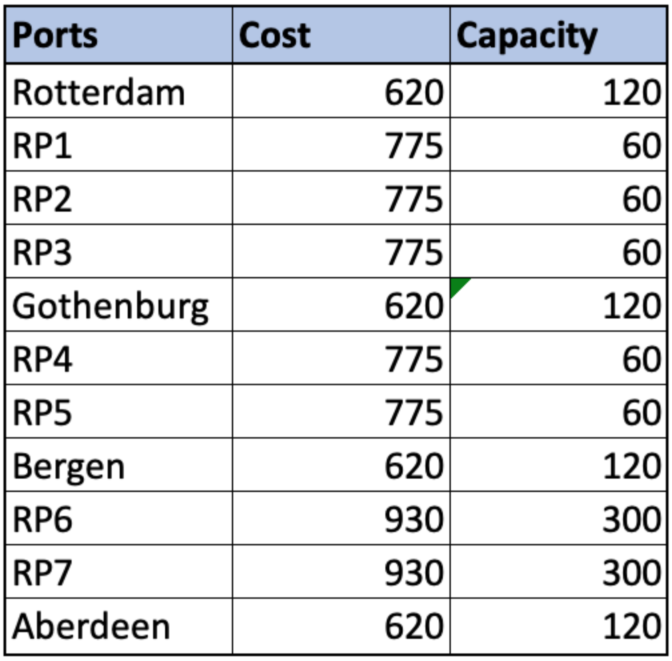
Appendix A

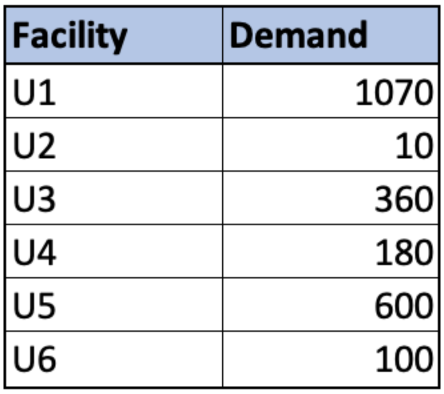
Excel Worksheet from North Sea case study

A.1 Reception points, cost and capacity



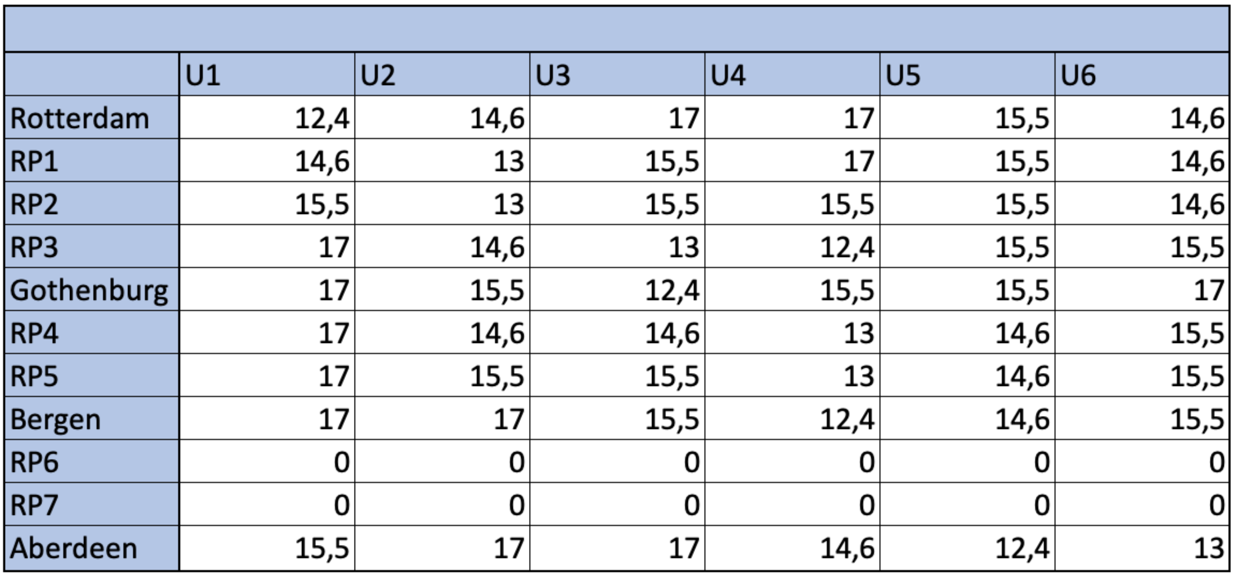
Ports	Cost	Capacity
Rotterdam	620	120
RP1	775	60
RP2	775	60
RP3	775	60
Gothenburg	620	120
RP4	775	60
RP5	775	60
Bergen	620	120
RP6	930	300
RP7	930	300
Aberdeen	620	120

A.2 Utilization facility, demand



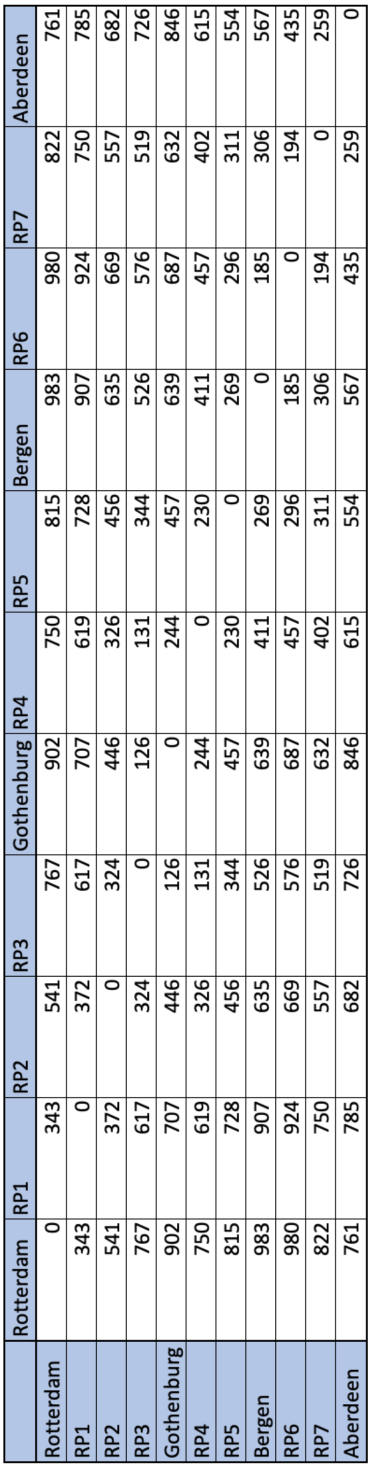
Facility	Demand
U1	1070
U2	10
U3	360
U4	180
U5	600
U6	100

A.3 Cost from reception point to utilization facility



	U1	U2	U3	U4	U5	U6
Rotterdam	12,4	14,6	17	17	15,5	14,6
RP1	14,6	13	15,5	17	15,5	14,6
RP2	15,5	13	15,5	15,5	15,5	14,6
RP3	17	14,6	13	12,4	15,5	15,5
Gothenburg	17	15,5	12,4	15,5	15,5	17
RP4	17	14,6	14,6	13	14,6	15,5
RP5	17	15,5	15,5	13	14,6	15,5
Bergen	17	17	15,5	12,4	14,6	15,5
RP6	0	0	0	0	0	0
RP7	0	0	0	0	0	0
Aberdeen	15,5	17	17	14,6	12,4	13

A.4 Distance matrix



	Rotterdam	RP1	RP2	RP3	Gothenburg	RP4	RP5	Bergen	RP6	RP7	Aberdeen
Rotterdam	0	343	541	767	902	750	815	983	980	822	761
RP1	343	0	372	617	707	619	728	907	924	750	785
RP2	541	372	0	324	446	326	456	635	669	557	682
RP3	767	617	324	0	126	131	344	526	576	519	726
Gothenburg	902	707	446	126	0	244	457	639	687	632	846
RP4	750	619	326	131	244	0	230	411	457	402	615
RP5	815	728	456	344	457	230	0	269	296	311	554
Bergen	983	907	635	526	639	411	269	0	185	306	567
RP6	980	924	669	576	687	457	296	185	0	194	435
RP7	822	750	557	519	632	402	311	306	194	0	259
Aberdeen	761	785	682	726	846	615	554	567	435	259	0

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