Tiril Amundsen

Optimization and impact assessment of urban waterborne transportation by modular vessels

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

Master's thesis

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

NTNU
Kunnskap for en bedre verden

Tiril Amundsen

Optimization and impact assessment of urban waterborne transportation by modular vessels

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

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

NTNU
Norwegian University of
Science and Technology

Master Thesis in Marine Systems Design – Spring 2022

Stud. techn. Tiril Amundsen

“Optimization and impact assessment of urban waterborne transportation by modular vessels”

Background

The transportation sector is facing strict regulations to reduce environmental impacts. To avoid further GHG emissions, effective waterborne transport systems must be developed to relieve road transport. Passenger ferries already provide public transportation by sea, but such transport systems often experience significant non-service gaps. If ferries could be utilized to transport cargo outside peak-commuting periods, emissions could potentially be reduced by moving road freight to the sea. Modularization technology could enable vessels to combine transportation of passengers and cargo by the ship only undergoing minor modifications.

Overall aim and focus

The candidate shall investigate technologies and concepts for urban waterborne transport combing transportation of passengers and cargo. A vessel concept and design features shall be established by using vehicle routing optimization. A multi-objective optimization model shall be developed and used in a case study to evaluate the economic, environmental, and social aspects of moving transportation from the road to the sea. Life cycle assessments shall be performed to assess environmental impacts.

Scope and main activities

1. Develop a vehicle routing optimization model for finding the optimal fleet size and routing of a waterborne transport system consisting of modular vessels alternately transporting commuting workers and cargo.
2. Develop a multi-objective optimization model to provide decision support to relevant decisionmakers when choosing a mode of transport.
3. Conduct life cycle assessments of a waterborne transport system and a road-based transport system to assess the global warming potential impacts.
4. Carry out computational studies for the fjord of Oslo to compare the performances of waterborne transportation with modular vessels to road-based transportation with private cars and trucks.
5. Present the results, and based on these, conclude on the potential for using modular vessels in short-sea shipping for combined transportation of passengers and cargo.

Modus operandi

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

Professor/Responsible Advisor

(This page is intentionally left blank)

Preface

Parts of the work conducted in this thesis are a continuation of the specialization project written in the fall semester of 2021. This mainly concerns a review of the literature regarding urban mobility, emissions from the transportation sector, and information on energy storage systems and autonomous operation of vessels.

The main motivation for the subject of this thesis is to explore innovative vessel concepts for making waterborne transportation competitive with road-based transportation in light of environmental, social, and economic aspects. The learning curve has been steep, but I have also had great use of subjects taught at the Department of Marine Technology at Tyholt, Trondheim, which I am grateful for.

I would like to thank my supervisor, Stein Ove Erikstad, for helping me shape the conducted work into the outcome presented in this master's thesis.

Tiril Amundsen

Tiril Amundsen

09.06.2022 Trondheim

Date

(This page is intentionally left blank)

Abstract

This master's thesis aims to investigate concepts for urban water transport systems combining transportation of passengers and cargo to increase efficiency and reduce costs and environmental impacts. It also seeks to assess the potential of a modal shift of transport in the fjord of Oslo, from road freight and the use of private cars to waterborne transport by modular vessels.

The optimal fleet size and routing of a waterborne transport system consisting of modular vessels have been found through a multi-commodity vehicle routing optimization model. Demand and supply of passengers and cargo have been defined for three locations; Nesodden, Slemmestad, and the central city of Oslo. Two modular vessels can fulfill the daily requirements where each vessel will undergo several configurations per day to switch between passengers' transportation and cargo distribution.

A multi-objective optimization (MOO) model has been developed to provide decision support to commuters and cargo owners when choosing a mode of transport. A road-based transport system consisting of private cars and conventional trucks has been compared to the waterborne transport system with regard to four criteria; Global warming potential (GWP), voyage duration, potential lead time, and cost of transportation. Life cycle assessments have been conducted for finding the GWP impacts from each transport system, and analytical hierarchy process (AHP) theory has been used to establish weight factors for each criterion.

The results of the computational studies indicate a great potential for combined waterborne transport of passengers and cargo in the fjord of Oslo, in terms of reduced environmental impacts and quality of service for both decision-makers. The solution is found to be robust for alterations in input parameters from performed sensitivity analyses. The findings of this thesis thus provide a foundation for further exploration of modularity in ship design.

(This page is intentionally left blank)

Sammendrag

Denne masteroppgaven har som mål å utforske konsepter for vannbaserte transportsystemer i urbane områder som kombinerer transport av gods og passasjerer for å øke effektivitet og redusere miljøpåvirkning og kostnader. Den har også som mål å evaluere potensialet av et modalskifte i Oslofjorden, fra veibasert godstransport og bruk av privatbiler til sjøtransport med modulære fartøy.

Optimering har blitt brukt for å finne den optimale flåtestørrelsen og hvilke ruter de modulære fartøyene i det vannbaserte transportsystemet skal seile for å minimere årlige kostnader. En daglig etterspørsel har blitt definert for tre lokasjoner; Nesodden, Slemmestad, og sentrum i Oslo. Det er funnet at to modulære fartøy kan dekke den daglige etterspørselen i Oslofjorden, ved at hvert fartøy gjennomgår flere konfigurasjoner for å operere i de ulike segmentene.

En multi-objektiv optimeringsmodell har blitt laget for å tilby beslutningsstøtte til pendlere og godseiere når de skal velge fremkomstmiddel. Et veibasert transportsystem bestående av privatbiler og konvensjonelle lastebiler har blitt sammenlignet med et vanntransportsystem bestående av modulære fartøy, med hensyn til fire ulike kriterier: globale oppvarmingspotensialer, reisetid, mulig ventetid/forsinkelser, og kostnad av fremkomstmiddel. Livssyklusanalyser har blitt gjennomført for å finne globale oppvarmingspotensialer for hvert transportalternativ. Analytiske hierarkisk prosesser har óg blitt gjennomført for å etablere vektfaktorer for hvert kriteria.

Resultatene fra multi-objektiv optimeringsmodellen indikerer et stort potensial for kombinert transport av passasjerer og gods i Oslofjorden ved bruk av modulære fartøy, i form av redusert klimapåvirkning og tilstrekkelig kvalitet på service for begge beslutningstakere. Gjennomførte sensitivitetsanalyser viser også at løsningen er robust og lite sensitiv til endringer i usikre input-parametere. Resultatene fra denne masteroppgaven gir dermed et grunnlag for videre forskning på bruk av modularitet i skipsdesign prosesser.

(This page is intentionally left blank)

Table of Contents

List of Figures

List of Tables

Abbreviations

AHP analytical hierarchy process.

GWP global warming potential.

LCA life cycle assessment.

MAS modular adaptable ship.

MCNF multi-commodity network flow.

MODA multi-objective decision analysis.

MOO multi-objective optimization.

TEU twenty-foot equivalent unit.

VRPMT multi-trip vehicle routing problem.

Chapter 1

Introduction

This master's thesis provides an approach for evaluating the potential of combined transportation of passengers and cargo in short sea-shipping by the use of new and innovative solutions challenging the former thinking and approaches in ship design. The thesis serves as further work for the specialization project written in the fall of 2021.

The transportation sector faces many challenges as regulations are setting stricter requirements by each year intending to reduce environmental impacts. Road transportation is the most common mode of domestic transportation for cargo distribution and passenger transport in the European Union (EU) and is responsible for over half of the environmental impacts of the transportation sector. To reach the goal of a climate-neutral EU by 2050, energy-efficient and reliable transport systems must be developed to replace conventional trucks and private cars. A modal shift in the transportation sector is suggested, where transport by inland waterways and short sea shipping is expected to help reduce greenhouse gas (GHG) emissions.

This thesis investigates transport systems and technologies that could enable the transition from distribution of cargo and passenger transport by trucks and private cars in urban areas while maintaining the flexibility and efficiency road freight provides and reducing global warming potential (GWP) impacts. The use of modularity in ship design has thus been explored, to increase the utilization of passenger ferries connecting suburban and urban areas in periods with low commuting activity. Computational studies have been conducted to evaluate the potential of vessels alternately transporting passengers and cargo by configuring a vessel to a specific task. The findings of this thesis serve to encourage further exploration of the use of modularity in ship design.

1.1 Trends in urban mobility

Cities are dominant centers of consumption and production, and more than half of the world's population live in urban areas, increasingly in highly-dense cities. Thus, they experience large movements of freight and passengers daily. Even though many large cities such as Oslo, Copenhagen, and Amsterdam are located by water, road transportation is generally the most common mode of transportation for both passengers and goods. In this section, trends in urban mobility will be discussed for both international and domestic transportation of passengers and cargo.

By investigating how goods are transported in Europe, it is found that road transportation is the most common mode of transport, even for countries with some of the largest inland waterways in Europe. Figure 1.1 shows statistics of how goods were transported in European countries in 2019 (UNECE 2022). The Netherlands, Belgium, and Germany are among the European countries with the largest networks of inland waterways. However, the percentage of cargo distributed domestically by waterborne transportation is still low.

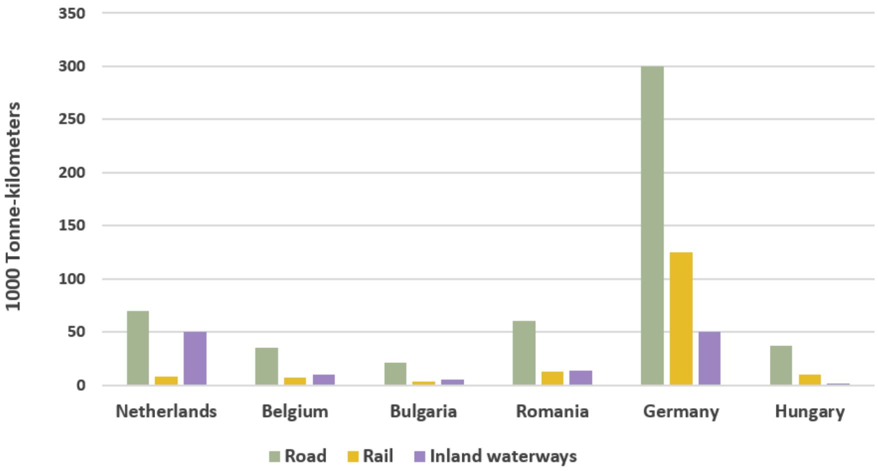


Figure 1.1: Freight tonne-kilometer by transport mode (UNECE 2022)

In The Netherlands, approximately 40% of the total freight tonne-kilometers registered in 2019 was through the use of waterborne transportation, and only 11% for Germany. It is also found that the vast majority of passenger transport at the EU level is undertaken by private cars (Pastori et al. 2018). This reflects a rather unexploited mode of transport.

1.2 The modal shift in transportation

The European Union has set several goals for increasing the resource effectiveness of transport systems, aiming to reduce greenhouse gas emissions by 90% by 2050. To reach their goals, a modal shift in the transportation sector is suggested with the aims of increasing transport by inland waterways and short sea shipping and phasing out the use of ”conventionally-fuelled” vehicles in major urban centers by 2050 (EC 2011).

Despite this, modal shift objectives are far from being met in practice. Statistics of freight moved in the EU between 1996 and 2016 show that the share of road transport has not decreased but rather increased slightly over the past 20 years. At the same time, sea transport and inland waterway transport have decreased by 0,8% and 0,2%, respectively (Pastori et al. 2018). Road freight usually provides more flexibility than waterborne freight in terms of offering door-to-door services and faster transit duration, making it difficult for short sea shipping to be competitive on its own (Pinchasik et al. 2020).

Maritime transport, including short sea shipping, is generally regarded as an environmentally friendly mode. Even though, regional and urban waterborne transport has not been competitive due to infrastructure overcapacity on land and a lack of offering the ”last-mile distribution”, i.e., transportation of either goods or passengers to the final delivery destination. In these cases, the European Commission wishes to expand the use of multimodal transport (EC 2022a).

Multimodal transport refers to the use of multiple modes of transport in the same journey, applying to both freight and passenger transport (EC 2022a). Even though maritime transportation might not enable door-to-door services in transportation, including it in a multimodal transport network could have benefits such as eased congestion on roads, reduced local emissions, and even reduced voyage duration for some cases. The European Union has 67000 kilometers of coastline and 25000 kilometers of navigable waterway. Maritime transport can reach peripheral regions which are difficult to reach by other transport modes.

Other advantages of integrating short sea shipping in a multi-modal transportation network include the fact that maritime transport uses a no-cost infrastructure, i.e., the sea. Port infrastructures require smaller investment budgets than rail and road infrastructure. Building bridges for enabling fjord crossings or for connecting smaller islands to the mainland requires much higher investment costs and maintenance compared to what ports do, which are the only land area needed for short sea shipping (ECMC 2001).

1.3 Master's thesis purpose and motivations

The main purpose of this master's thesis is to investigate the possibility of developing and taking into use modular vessels in short sea shipping, which combine transportation of passengers and cargo through the use of advanced modular technologies. This master's thesis also aims to provide decision support to commuters and cargo owners for evaluating the utility of an urban water transport system consisting of modular vessels compared to a road-based transport system consisting of conventional vehicles, battery-electric vehicles, and conventional trucks.

The main motivation for investigating the potential of modular vessels combining transportation of passengers and cargo in short sea shipping is to explore more environmentally friendly modes of transport for reducing greenhouse gas emissions. Another key driver is to explore how vessels can be utilized to a greater extent by combining transportation of different commodities. Passenger ferries connecting suburban areas to city centers often experience non-service gaps between peak commuting periods in the morning and the afternoon. Utilizing the vessels to transport cargo in these periods could potentially contribute to reductions in global warming potential impacts for cargo owners by substituting cargo transportation by trucks with waterborne transportation, and a reduction of expenditures for ferry operators in terms of investment costs, operational expenses, and port charges.

1.4 Scope and limitations

The scope of this master's thesis is to evaluate the potential of waterborne transportation in short sea shipping through the use of modular technology. The objective of this thesis can be summarized by the following research questions:

- Can transportation of passengers and cargo be combined through the use of advanced modular technology?
- What kind of design considerations at an early-stage planning process is important for enabling this concept?
- How does an urban water transport system consisting of electric modular vessels perform compared to a road-based transport system consisting of ICEVs, EVs, and conventional trucks?

The main limitations in this thesis are related to the availability of required data for conducting computational studies for the case study. As of today, the use of modular technology in ship design is relatively unexplored. Thus, several assumptions have been made throughout this Master's thesis regarding cost coefficients and operational considerations for the modular vessels which might not be fully representative of a real-world system. Additionally, the process of gathering required data for conducting fully representative life cycle assessments of the transport systems is quite time-consuming. Thus, the LCAs have been limited to only represent the emissions from the major contributors within each lifecycle stage, found from previously performed LCAs studied in the literature review.

1.5 Structure of the report

The current chapter presents the purpose and motivations for the thesis, in addition to the scope and limitations of the used approaches and the conducted computational studies. Chapter 2 elaborates on challenges the transport industry is facing today and provides an overview of patterns in urban mobility. It also provides a discussion of the potential advantages of short sea shipping. In Chapter 3, a literature review is conducted where existing research on modularity in ship design and the use of urban water transport systems is presented. It also presents literature relevant for multi-objective optimization, multi-commodity vehicle routing optimization, and research on existing conducted life cycle assessments relevant for this thesis.

In Chapter 4 and Chapter 5 the developed multi-objective optimization model and multi-commodity vehicle routing model are presented, respectively. The purpose of the optimization models and an explanation of the model formulations and the required input is elaborated on as well. The methodology for conducting a life cycle assessment is presented in Chapter 6. The goals and scope of the LCAs are also included in this chapter. Chapter 7 presents the case study of this master's thesis and provides information on the decision-makers in the case, the defined criteria that the alternative transport systems will be compared within, and information on the alternative transport systems. Chapter 8 further elaborates on design considerations for the modular vessels and presents an early-stage description of the modular vessels in terms of main dimensions, load capacities, and operational features. The required input for computational studies for the case study is presented in Chapter 9.

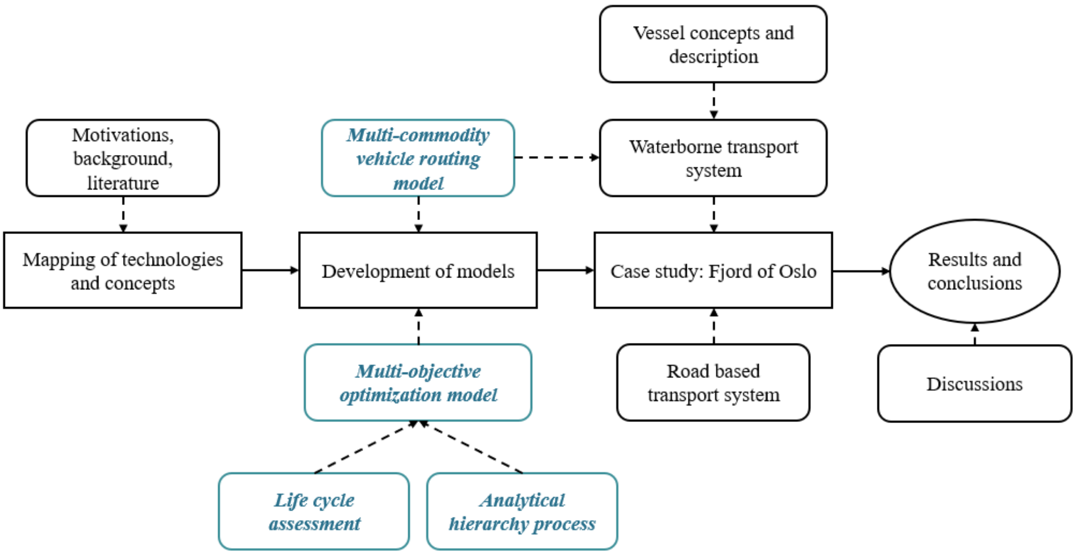


Figure 1.2: An illustration of how the approaches presented in this thesis is used for obtaining results. Blue boxes refer to methods, models, and approaches.

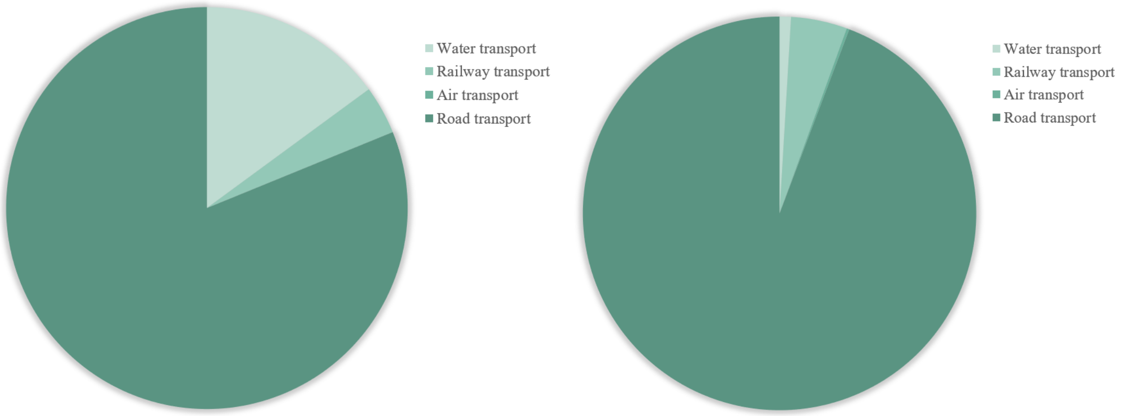
Figure 1.2 illustrates how the approaches and methods presented in the former chapters are used for obtaining the results presented in Chapter 10. The obtained results, and the methodologies and approaches used in this master's thesis, will be discussed in Chapter 11, and proposals for further work are included. Chapter 12 concludes the thesis.

Chapter 2

Background

2.1 Urban mobility in Norway

Road transportation is the most common mode of domestic transportation for both passengers and cargo in Norway. Figure 2.1 presents statistics of how goods and people were transported in Norway in 2019 (SSB 2020). Over 80% of the total distributed cargo in 2019 was transported by vehicles on roads. Road transportation also accounted for nearly 95% of the total number of passengers traveling in Norway.



(a) Of goods, in tonnes. **(b)** Of people, in passengers.

Figure 2.1: Domestic transportation in Norway (SSB 2020).

Norway is among the top ten countries in the world with the longest coastline, ranking in fifth place with a total of 25 000 km of coastline (Statista 2021). The many fjords of Norway contribute to the long coastline, dividing populated areas by water. Thus, waterborne transportation has a great potential domestically in Norway for the distribution of cargo and transportation of passengers along the coast. Despite this, statistics show that a much larger share of cargo is transported by road, as shown in Figure 2.1a.

2.1.1 Commuting activity in urban areas

Another interesting aspect to investigate related to urban mobility is the influence of commuters. The average commuting duration for employees in the European Union (EU) is approximately one hour a day, either by public or private transportation (EC 2020). As seen from Figure 2.1b road transportation accounted for nearly 95% of the total registered passengers in Norway in 2019, where usage of private cars was by far the most common mode of transportation. Public transportation accounted for only 13% of the measured passenger activity, with ferry transportation obtaining the minor share (SSB 2022a). Thus, it is not unreasonable to assume that usage of private cars is the most common mode of transportation for commuting workers in Norway.

Oslo is an example of a city that experiences significant commuting from nearby communes, or suburban areas, many of which are located nearby water. Figure 2.2 shows statistics of commuting into Oslo from the ten largest contributors, where Bærum is the largest contributor with almost 27 000 registered commuters in 2017.

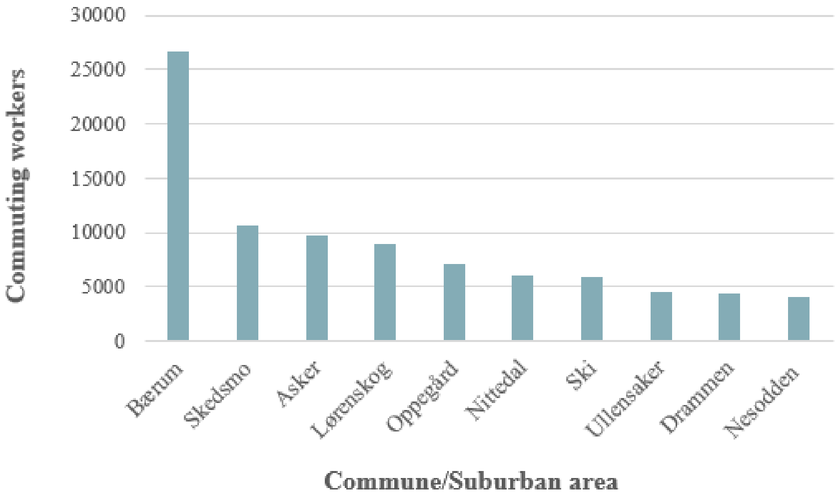


Figure 2.2: Statistics of commuting activity into Oslo from nearby communes (Kommuneprofilen 2022).

Based on the geography of Oslo and the surrounding areas, it could be suitable with waterborne transportation from several of the communes into the city center. Of the ten largest contributors, Asker, Bærum, Oppegård, and Nesodden are located near water. Today, a ferry system provides waterborne transportation services from

Asker and Nesodden to the city center, with frequent departures in the morning and the late afternoon when commuting activity is at its highest.

2.2 Emissions from the transportation sector

The European Green Deal, developed under the initiative of the European Commission, is a set of policy initiatives to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 and a long-term goal of becoming climate neutral by 2050 (EC 2022b). The transportation sector is responsible for approximately a quarter of the total GHG emissions in the European Union, and the sector is the main cause of air pollution in cities. This section will investigate the environmental impacts of the road transportation sector and waterborne transportation sector.

2.2.1 Road transportation

Road transportation is by far the most significant contributor to GHG emissions in the EU, accounting for nearly 75% of the impacts from the transportation sector. Figure 2.3 provides an overview of GHG emissions to air in Norway from different sectors. Road traffic makes up 17% of the total emissions and is thus the third largest contributor to GHG emissions in Norway (SSB 2021).

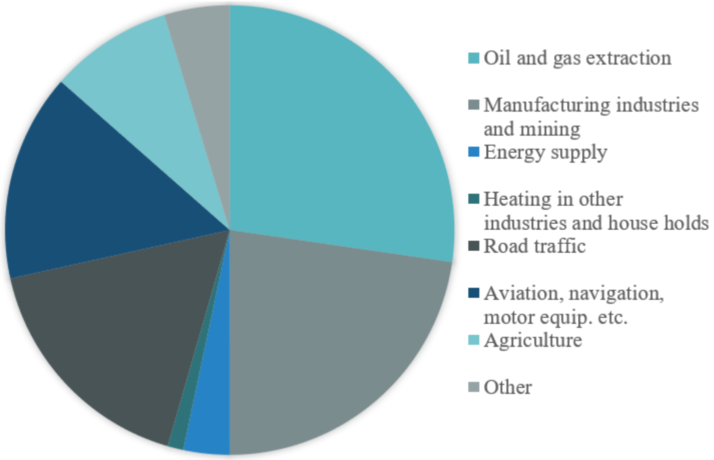


Figure 2.3: Greenhouse gas emissions to air in Norway (SSB 2021).

City centers are known for experiencing large amounts of traffic in specific periods, usually in the morning and late afternoon, when commuting activity is at its highest. Distribution of goods in cities mainly happens during the day, when the load on the infrastructure is highest. Trucks contribute to increasing queues on the roads, resulting in ineffective operation and increased environmental impacts from the road transportation sector. The EU has set high ambitions for the distribution of goods in large cities to be climate-neutral by 2050. However, the increased urbanization will lead to higher consumption in cities and thus a higher demand for imported goods (Andersen et al. 2021). Finding new and environmentally friendly solutions for the transportation of goods will be crucial to balance the increasing urbanization and achieve a climate-neutral distribution of goods in the future.

2.2.2 Waterborne transportation

Ships entering ports in the European Union emit approximately 13% of the total EU transport emissions (WTP 2021). The sector is responsible for 3% of the global GHG emissions. Under a business-as-usual scenario, a GHG study conducted by the International Maritime Organization (IMO) estimates that shipping emissions could increase between 90% and 130% by 2050 of 2008 emissions (IMO 2020). The key problem drivers in shipping are listed below:

- As waterborne transport is an international sector new solutions will have to be supported internationally.
- New standardized solutions are difficult to implement due to a large diversity in the sector and long lifetimes combined with task-oriented design thinking.
- There is a lack of affordable and available fuel alternatives in ports worldwide.

Despite this, waterborne transportation is considered a much more environmentally friendly transport mode than road transport. Freight transport by waterborne transportation is almost 20 times more GHG efficient than road transportation, mainly because transportation by vessels allows for larger quantities of cargo to be transported per voyage (EEA 2022). The primary motivation for the suggested modal shift in the transportation sector is the increased GHG efficiency.

2.3 Challenges in short-sea shipping

Several challenges arise when discussing transportation of cargo and passengers in short-sea shipping. Some of the major challenges are related to relatively low cargo volumes through ports and the low utilization rate of passenger ferries in periods with low passenger traffic.

As previously discussed, the main mode of transport for domestic transportation of cargo is road freight. Table 2.1 shows that a total of 746 twenty-foot equivalent unit (TEU)s were unloaded in the port of Oslo in 2018, which equals a daily rate of approximately two incoming TEUs. In short-sea shipping, port fees and cargo handling usually make up a larger share of the voyage costs than in deep-sea shipping, as shorter distances are sailed, and more frequent port visits are expected. Thus, stable and large enough cargo flows are crucial for vessels operating in short-sea shipping to maintain steady revenue streams to cover repayment of investment costs and daily expenditures.

Table 2.1: Domestic incoming and outbound goods to and from Oslo in 2018 by maritime transport, given in tonnes (SSB 2018).

	Loaded	**Unloaded**	**Total**
Incoming	728	18	**746**
Outbound	1339	18 886	**20 225**

According to Tanko et al. (2018), it can be challenging to achieve a long-term economically viable service for passenger ferries connecting suburban and urban areas because of the dominating peak commuting periods in the morning and the late afternoon. In between these periods, the operating vessels often experience a non-service gap. These periods can be costly due to little or no incoming revenues combined with port fees, a significant component of operational expenditures in short-sea shipping. In addition, ticket costs can only be increased to a certain degree for ferries to be competitive with transportation by private vehicles, consequently limiting the incoming revenues for ferry operators.

2.4 Decision-making in the transport sector

Seven steps are identified for decision-making processes, illustrated in Figure 2.4. Decision-making is an iterative process as the final decision will be evaluated against the decision problem defined in the first step. If the results do not meet the identified need, several steps may have to be repeated until the final result fulfills the requirements of the problem. Thus, decision-making can be quite time-consuming and require comprehensive work to obtain satisfactory results when dealing with complex problems.

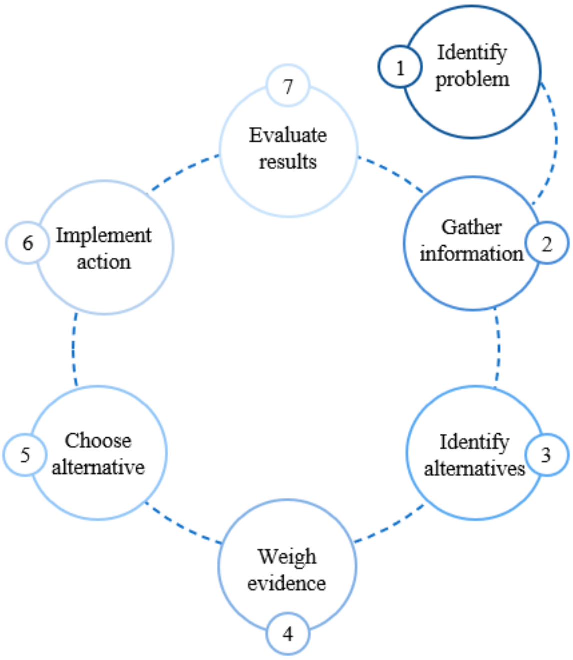


Figure 2.4: The seven steps of decision-making processes (Shaqiri 2014).

The transportation sector faces strict requirements for environmental impacts, causing a need for innovative design solutions to substitute conventional fossil-fueled vehicles. However, sustainable developments must also be economically viable and socially acceptable. Economic benefits must be greater than the costs related to the project, and the quality of the service must be sufficient to fulfill the users' needs and expectations. The balance between these requirements can be challenging to define, especially when multiple stakeholders are involved.

Decision-making in the transport sector is challenging due to complex interrelationships between political, social, and environmental aspects. In general, multiple decision-makers and stakeholders are affected by the choices made in the transportation sector, such as national authorities, residents, distributors, suppliers, and so on. Thus, there is a general need for robust and effective decision-support tools for ensuring optimal solutions satisfying the relevant decision-makers involved.

Chapter 3

Literature review

This chapter provides an overview of relevant literature for modeling maritime transportation systems, multi-commodity network flow (MCNF) problems, and multi-objective optimization (MOO) models. It also presents information on the use of modular technology in the maritime industry, urban water transport systems in general, and its use worldwide today. The methodology for performing an analytical hierarchy process (AHP) is also presented in this chapter, in addition to literature and research on conducted LCAs of road-based and waterborne transport systems.

3.1 Modular adaptable ship design

Modular adaptable ship (MAS) design is a known concept that has received growing attention in the last decades. According to Choi et al. (2018), MAS design is an approach for designing value-robust vessels that can maintain their value throughout their lifecycle. By using modular technology, a MAS can change its configuration by recombining and separating modules. Such modules can be divided into standard ship modules and task-related modules. Standard modules include the main hull, deckhouse, and bridge, and task-related modules include the equipment needed for performing specific tasks. The modules of a MAS serve as an operation platform, which is used as a common basis for multiple module configurations. The term product platform is well known in engineering design and is a common basis for numerous products or mass customization. An operation platform is a common basis for multiple configurations of a flexible product (Choi et al. 2018).

One of the main purposes of using modular adaptable ship design is to maximize profit. The design approach provides decision-makers strategic options for handling contextual uncertainty in ship design. Examples of uncertain contextual factors in ship design are technology maturity, economic, future demand, and regulatory. These factors are difficult to predict and are usually highly influential for the viability of a project. Erikstad (2009) points out other potential benefits of modular architectures as the combination of short lead time, rapid configuration, and flexibility in customization.

3.1.1 Modularity in ship design

Ship design is complex due to highly customized requirements and extensive interrelationships between different systems. Thus the application of modularization has been limited in the general ship design process. Shipbuilding has previously had a focus on individual projects rather than process improvements (Erikstad 2009). This section highlights shipyards and ship designers that have included modular technology and methods in their ship design processes.

TrAM - Transport: Advanced and Modular

Several European ship designers and shipyards participate in the innovative TrAM project, to develop a zero-emission fast-going passenger vessel through advanced modular production. The project is revolutionary in using advanced modularisation technology, which will allow for external variety in the form of enabling individual modules to be combined so that subsequent vessels can be adapted to specific customer requirements. The project also seeks to promote the possibility of reusing modules across vessels, which can allow for faster development and production (TrAM 2021). Figure 3.1 shows how the modules can be configurated for different purposes.

Figure 3.1: Concept for modular vessel Medstraum (TrAM 2021).

The zero-emissions passenger ferry will operate in Stavanger and in the rivers and channels in London and Belgium. In Stavanger and London, the passenger module will be used to transport passengers, and in Belgium, this module is removed to transport cargo directly on the main deck.

The TrAM project is also looking into possibilities for integrating a modular power supply. In previous ship designs, batteries and power electronics have usually been stored inside the hull, but TrAM wants to store these on the upper level of the vessel instead. According to modular expert Seidenberg (2021), battery technology will develop rapidly in the coming years, and having the power module as an easily accessible unit can potentially benefit future retrofitting.

Ulstein Verft: Standardised modules

The shipyard Ulstein Verft has a long experience designing ships, and conceptualizing and realizing conversions, upgrades, and retrofits of existing vessels. In recent years the shipyard has invested in the use of modularity in shipbuilding, which they claim will be a cost-efficient solution for ship owners in the years to come (Ulstein 2019).

Ulstein Verft aims to use pre-manufactured modules to mobilize vessels for other types of work without intervening in the ship structure. Additionally, the modules can be adapted to a customer's specific requirements if the existing ones do not fit the criteria. When missions are completed, the modules can easily be demounted and reused on other vessels with only minor adjustments. The shipyard has already developed predefined modules for two of their ship designs, both being platform supply vessels (Ulstein 2019).

3.1.2 Types of modularity

According to Ulrich and Eppinger (2016), three basic types of modularity are identified; Slot-modular architecture, sectional-modular architecture, and bus-modular architecture. An illustration of the different types can be seen in Figure 3.2. Slot-modular architecture is characterized by each of the interfaces between the modules being different from the others. The various modules can not be interchanged, meaning that the interface of one module is different from any of the other components. Slot-modular architectures are the most common of the modular architectures.

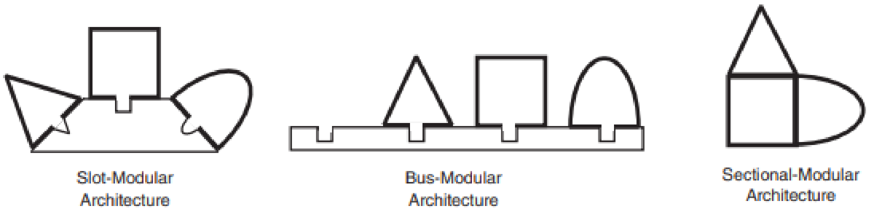


Figure 3.2: The three types of modularity (Ulrich et al. 2016).

In sectional-modular architecture, all interfaces are of the same type, but there is no single element to which the other modules attach. In other words, there is no "platform" to which the other modules attach. Instead, the assembly is built up by connecting the modules via identical interfaces. All modules have one or a few common interfaces, which typically allow a more extensive variety in the physical layout of the product.

In bus-modular architecture, there is a standard part to which the other modules connect via the same type of interface. The interface is standardized across several module types. This type of modularity is required when different selections and combinations of equipment modules are used to customize the product for various purposes. In this thesis, the bus-modular architecture will be further explored.

3.2 Urban water transport systems

Many variants of waterborne transport systems for transportation of passengers and cargo exist all over the world. Operation pattern and fleet composition highly depend on the type of cargo to be transported, the demand of potential customers or passengers, and the geographical features of the area where the transport system is located.

Urban water transport systems often complement land-based transportation systems and play a vital role in the supply chains of domestic distribution of cargo. Other systems primarily function as an alternative for public transport, providing transport services to passengers over shorter and longer distances. This section investigates and maps various urban water transport systems existing worldwide today.

3.2.1 Transportation of passengers

In many large cities worldwide, waterborne transport systems are used to connect suburban areas to urban areas or city centers. Tanko et al. (2018) characterize these systems by operating at high frequencies in certain peak commuting periods, which typically are in the morning and the late afternoon. In large cities like Hong Kong, Auckland, Rio de Janeiro, and Seattle, ferry systems connect smaller islands to the mainland and suburbs to city centers. These ferries have frequent passenger departures in peak commuting periods and fewer departures in off-peak periods. Many of the ferries operating these routes are high-speed passenger catamarans, with some monohull ferries capable of carrying cars.

3.2.2 Transportation of cargo

Inland waterway transport plays an essential role in transporting goods in Europe. According to the European Commission (2003), approximately 6% of all goods transported in the EU are carried by inland waterways, even though Europe has over 30 000 kilometers of rivers and canals connecting large cities and central areas of industrial concentration. Several of the largest European waterways are located in the Netherlands, Belgium, and Germany, such as the Rhine River, Schelde River, and Elbe River. The percentage of goods transported by inland waterways in these countries ranges from 10% and up to almost 40%, as seen in Figure 1.1, reflecting an under-exploited mode of inland transport.

3.3 Literature relevant for the multi-objective optimization model

Multi-objective decision analysis (MODA) is a branch of operations research used for evaluating a decision problem under multiple objectives or criteria based on a set of underlying values belonging to the decision-makers. Decision-makers confront difficult decisions daily and must consider an increasingly wide range of criteria in making those decisions. In the past, such decisions were often judged only based on a single attribute, such as profit or cost. However, these attributes do not fully capture the desirability of a decision alternative. MODA is therefore highly relevant for decision-makers seeking to find optimal solutions when dealing with multiple criteria (Scala et al. 2012). Approaches and methods for dealing with multi-objective decision problems will be investigated in this section.

3.3.1 Multi-objective optimization

Multi-objective optimization (MOO) problems, also known as multi-criteria optimization, involve more than one objective function to be minimized or maximized. The answer is a set of solutions that define the best trade-off between competing objectives. Caramia et al. (2008) present the following general form of the multi-objective optimization problem.

$$min\{f_1(x), f_2(x), \ldots, f_i(x)\}, \tag{3.1}$$

$$Subject\ to:$$

$$x \in \mathcal{S} \tag{3.2}$$

where x is a solution or an alternative, $\mathcal{I}$ is the set of objectives, $f_i(x)$ is the i_{th} objective function, and $\mathcal{S}$ is the set of constraints that can be defined as

$$\mathcal{S} = \{x \in \mathcal{R}^i : h(x) = 0, g(x) \geq 0\}. \tag{3.3}$$

3.3.2 The weighted-sum method

Classic multi-objective optimization methods include the weighted-sum method, also called the scalarization method. Caramia et al. (2008) propose the following weighted-sum model formulation for a MOO problem.

$$minF(x) = \sum_{i \in \mathcal{I}} w_i f_i(x), \tag{3.4}$$

$$Subject\ to:$$

$$\sum_{i \in \mathcal{I}} w_i = 1, \tag{3.5}$$

$$w_i \geq 0, \quad \forall i \in \mathcal{I}, \tag{3.6}$$

$$x \in \mathcal{S} \tag{3.7}$$

where w_i is the weight vector chosen by the decision-maker. The method aims to combine a problem's multiple objectives into one single-objective scalar function by considering a defined objective weight chosen in proportion to the relative importance of the objective. However, it can be challenging to establish the relative importance of each objective. In such cases, value theory methods can be helpful, as presented in the next section.

3.3.3 The analytical hierarchy process

The analytical hierarchy process (AHP) method allows the user to identify the criteria and the alternatives to be considered in the potential solution of the decision problem. The evaluation of the alternatives against the objectives considers both subjective and objective information to determine the preferred option among a set of alternatives. The method requires the decision-maker to express the level of preference between different objectives using a scale (Guerra et al. 2014).

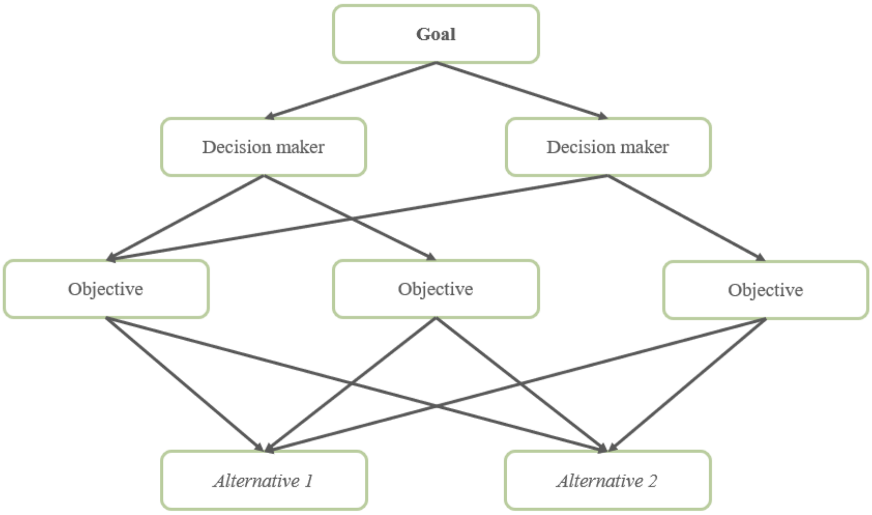


Figure 3.3: The hierarchical structure of an AHP.

The first level of the hierarchical structure corresponds to the overall goal of the decision problem. The second level consists of the decision-makers, the objectives, and potential sub-objectives considered in the problem. The number of decision-makers depends on the context and the interested parties with enough power of decision. The objectives are the important aspects relevant to the goal. The third level of the hierarchical structure consists of the alternatives.

The analytical hierarchy process uses a pairwise comparison. The objectives and the possible alternatives are first to be determined, and for each objective, a pairwise comparison between the alternatives must be made. These comparisons identify the level of preference between the options in each objective through a numerical scale, presented in Table 3.1 (Guerra et al. 2014).

Table 3.1: Preference scale for the AHP method.

1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred

When the comparisons are made the values are inserted in a pairwise comparison matrix. The elements in the comparison matrix represent the importance of one objective relative to another. The general layout of such a matrix can be seen in Equation 3.8.

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & a_{nn} \end{bmatrix} \tag{3.8}$$

When the comparison matrix is established, the vector of objective weights can be found. The comparison matrix must be normalized, and the principal eigenvector of the matrix must be calculated. Then, the vector of objective weights can be found by normalizing the principal eigenvector. Each entry in the vector can be found by using Equation 3.9 (Guerra et al. 2014).

$$w_i = \frac{\sqrt[m]{\prod_{j=1}^{m} P_{ij}}}{\sum_{i=1}^{m} \sqrt[m]{\prod_{j=1}^{m} P_{ij}}} \tag{3.9}$$

where j indexes the columns and i the rows in the comparison matrix. When the weight vector w is established, it can be used as input in the classical weighted-sum model presented in the previous section.

3.4 Literature relevant for multi-commodity vehicle routing model

Optimization has been used for finding the optimal fleet size and routing for an urban water transport system consisting of modular vessels transporting passengers and cargo. The vehicle routing problem in this thesis consists of finding the optimal fleet and routing for vessels sailing multiple routes with multiple commodities.

Thus, literature on multi-commodity network flow (MCNF) problems and multi-trip vehicle routing problems (VRPMT) will be presented in this section.

3.4.1 Multi-commodity network flow

The multi-commodity network flow (MCNF) problem is defined over a network where multiple commodities need to be transported from specific origin nodes to destination nodes while not exceeding the capacity constraint associated with vessels and arcs. There are mainly three different MCNF problems that are applied in literature; the $max\ MCNF$ problem, the $max - concurrent\ flow$ problem and the $min - cost\ MCNF$ problem. Wang et al. (2018) has developed a binary min-cost MCNF model formulation, which aims to find the flow assignment satisfying the demands of all commodities with minimum cost without violating the capacity constraints on all arcs. In this formulation, each commodity can only be shipped on one path.

The arc-path formulation

For commodity k, $\mathcal{P}^k$ denotes the set of all possible paths from origin s_k to destination t_k. $\mathcal{A}$ is the set of arcs, indexed by a. f_p represents the units of flow on path $p \in P^k$, and C_p^c represents the cost of path p when transporting commodity c. δ_a^p is a binary indicator which equals 1 if path p passes through arc a, and 0 otherwise.

The arc-path model formulation of the multi-commodity network flow problem can be seen in Equation 3.10-3.13.

$$min \sum_{k \in \mathcal{K}} \sum_{p \in \mathcal{P}^k} C_p^c f_p \tag{3.10}$$

$$Subject\ to:$$

$$\sum_{p \in \mathcal{P}^k} f_p = 1, \quad \forall k \in \mathcal{K} \tag{3.11}$$

$$\sum_{k \in \mathcal{K}} \sum_{p \in \mathcal{P}^k} (B^k \delta_a^p) f_p \leq u_a, \quad \forall a \in \mathcal{A} \tag{3.12}$$

$$f_p \geq 0, \quad \forall p \in \mathcal{P}^k, \forall k \in \mathcal{A} \tag{3.13}$$

The objective function (3.10) minimizes total transportation costs. Constraint (3.11) is the convexity constraint forcing the optimal solution for each commodity k to be a convex combination of some simple paths in P^k. Constraint (3.12) ensures that the capacity on arc a is not exceeded. Constraint (3.13) ensures that the units of flow on each path is positive (Wang 2018).

3.4.2 Multi-trip vehicle routing problem

Fagerholt (1999) has proposed a method for finding the optimal fleet size for a liner shipping problem considered as a multi-trip vehicle routing problem (VRPMT). The VRPMT is an extension of the standard vehicle routing problem (VRP) with time constraints. The vehicles may perform several routes as long as the total duration of the routes for each vehicle does not exceed a given time limit. Similar to the standard VRP, the VRPMT requires that each node shall be visited once and only once. The method used to find the optimal fleet size is called the set partitioning approach, which consists of the following two steps:

1. Generation of candidate schedules/routes for the vessels in the fleet.
2. Solving a master problem for finding the best combination of the candidate schedules/routes for the fleet.

Fagerholt (1999) has developed a route generation algorithm for generating single routes and a combination of these into multiple routes. The first step is to develop all feasible single routes, i.e., routes that do not exceed the duration limit. Then all feasible combinations of two single routes can be found, which become 2-routes. Then the single routes generated in the first step can be combined with the 2-routes into 3-routes, and so on, until no new multiple routes can be generated due to time constraints.

The set partitioning problem formulation

$\mathcal{R}_v$ is the set of all routes (both single and multiple routes) which is generated, indexed by r. $\mathcal{N}$ is the set of nodes, or ports, to be serviced by the fleet of vessels, indexed by i. C_r is the cost of choosing route r, which often consists of time-charter costs, sailing costs, and other operational costs. A_{ir} is a constant which equals 1 if route r services node i and 0 otherwise. x_r is a binary variable that equals 1 if route r is chosen in the optimal solution and 0 otherwise.

The master problem for the multi-trip vehicle routing problem can be seen in Equation 3.14-3.16.

$$min \sum_{r \in R} C_r x_r \tag{3.14}$$

$Subject\ to:$

$$\sum_{r \in R} A_{ir} x_r = 1, \quad \forall i \in \mathcal{N}, \tag{3.15}$$

$$x_r \in \{0, 1\}, \quad \forall r \in \mathcal{R} \tag{3.16}$$

The objective function (3.14) minimizes the total sailing costs for the fleet of vessels and the routes r. Constraint (3.15) ensures that each node i is serviced exactly once by a vessel in the fleet, and constraint (3.16) includes the binary requirement (Fagerholt 1999).

3.5 Literature relevant for life cycle assessment

Life cycle assessment will be used for finding the global warming potential (GWP) impacts of the transport systems under investigation. This section contains information on previously performed LCAs of road vehicles and electric ferries and aims to map the major contributing processes to GWP impacts for road-based transport and waterborne transport.

3.5.1 Life cycle assessments of electric ferries

Galaaen (2020) and Kullmann (2016) have both performed comprehensive cradle-to-grave LCAs of both diesel-electric and all-electric ferries. For the battery-electric case, Galaaen found that the operation phase and the phase of constructing the ferry contributed the most to global warming potential. Within the construction phase, the major contributor to CO_2 emissions was the extraction of materials needed for constructing the hull and the superstructure. In terms of the operational GWP impacts, the major contributors were electricity production from natural gas using a conventional power plant and hard coal heat and power co-generation. According to Galaaen (2020), the GWP impacts of the battery-electric ferry were lower compared to the diesel-electric ferry mainly due to the avoided direct emissions and impacts from the diesel fuel value chain.

Kullmann's (2016) findings from the comparative LCAs support Galaaen's results. The operation phase of the electric ferry was the most significant contributor to GWP impacts. The second largest contributor was, in similarity to Galaaen's findings, the construction of the hull due to the extraction of required material, mainly steel. The third largest contributor was developing and constructing the required batteries and the propulsion system. Kullmann also did a study on how the usage of different electricity mixes influenced the environmental impacts of the electric ferry. By using a Norwegian electricity mix, the GWP impacts were reduced by approximately 70% compared to the usage of a UCTE electricity mix and by almost 90% compared to the use of a Chinese electricity mix (Kullmann 2016).

3.5.2 Life cycle assessments of road vehicles

Ellingsen et al. (2016) have performed cradle-to-grave life cycle assessments of electric vehicles (EVs) to investigate the effect of increasing battery size and driving range on the environmental impact and internal combustion engine vehicles (ICEVs) to compare the life cycle emissions. For the EVs, the major contributors to GWP impacts were the operation phase of the vehicles, indirectly through the production of electricity, and the production phase due to extraction of required material. Production of the required battery was the third largest contributor. For the ICEVs, the production phase of the vehicles was less environmentally intensive, mainly due to the production of the batteries for the EVs. The operation phase accounted for most of the GWP impacts for the ICEVs. Compared to the EVs, the impacts were approximately twice as large. End-of-life phases for both vehicles accounted for less than 4% of the total GHG emissions (Ellingsen et al. 2016).

Espegren et al. (2021) have performed a cradle-to-grave LCA of a conventional truck, i.e., a fossil-fueled internal combustion engine truck powered with diesel, with a gross vehicle weight of 12 tonnes and a lifetime of 12 years. The operation phase was the largest contributor to GWP impacts, with emissions accounting for approximately 65% of the total impacts. The contributions of the fuel-production distribution phase accounted for approximately 24% of the GWP impacts, making it the second largest contributor. The production and assembly of the truck was the third largest contributor (Espegren et al. 2021).

Chapter 4

Multi-objective optimization model

As discussed in Chapter 2, decision-making in the transport sector can be difficult due to the complex interrelationships between political, social, and environmental aspects. In addition, several stakeholders and decision-makers require involvement in the decision-making processes, leading to multiple objectives, constraints, and preferences that need to be considered. Efficient and comprehensive decision support tools are thus vital for saving time, workloads, and expenditures when dealing with complex projects.

A deterministic multi-objective optimization (MOO) model has been developed to provide decision support to relevant decision-makers choosing means of transport, based on the preferences of the decision-makers and the utility of each alternative within each criterion. The utility refers to the performance indicator of the alternative transport system, i.e., how well the system performs compared to a standard. This chapter elaborates on the intention and formulation of the model and explains the required input for performing computational studies of a given case.

4.1 Problem definition

The purpose of the multi-objective optimization model is to evaluate alternative transport systems with regards to their performance and the preferences of the relevant decision-makers among a set of criteria they consider important when choosing a mode of transport. The weight factors aim to take the decision makers' preferences into account when finding the optimal solution for a mode of transport for distribution of cargo and transportation of passengers.

The transport systems to be evaluated are a road-based transport system consisting of private cars for passenger transport and trucks for freight transport, and a waterborne transport system consisting of modular vessels alternately transporting passengers and cargo. The decision-makers are commuting workers and cargo owners, and the chosen criteria to be evaluated are global warming potential (GWP) impacts, voyage duration, potential lead time, and cost of transportation.

Figure 4.1 illustrates the process of finding the optimal mode of transport for decision-makers with regards to performances and weight factors set by the decision-makers.

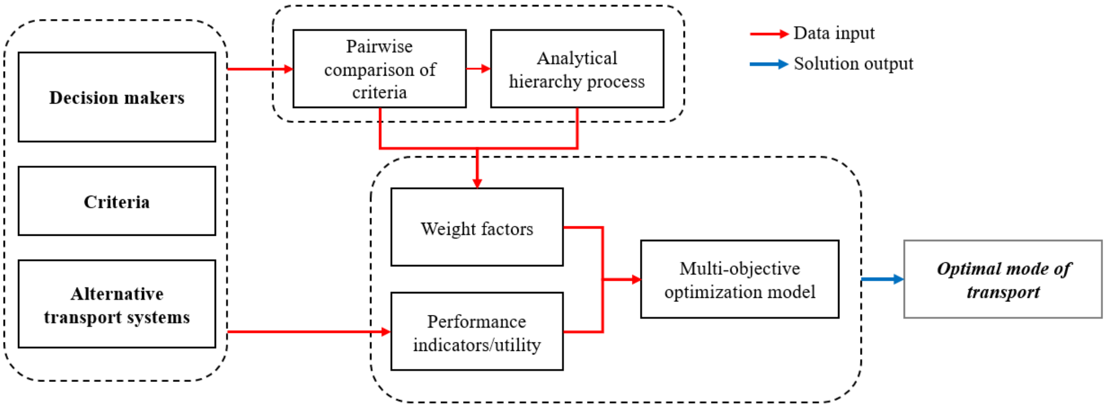


Figure 4.1: The process of finding optimal mode of transport by using the defined multi-objective optimization model.

4.2 Formulation of multi-objective optimization model

The developed optimization model has the same structure as the weighted-sum model, presented in Chapter 3. The purpose of the model is to return the favored transport system based on the performances of the alternatives within each criterion and weight factors set by the decision-makers. The weight factors will be calculated through the use of the analytical hierarchy process (AHP) method, also presented in Chapter 3, by using a pairwise comparison of each criteria performed by the decision-makers. The following model notation and formulation have been used to model the MOO problem.

Multi-objective optimization model notation:

Sets		
$\mathcal{A}$	...	Set of alternatives, denoted a
$\mathcal{D}$	...	Set of decision makers, denotes d
$\mathcal{C}$	...	Set of criteria, denoted c
$\mathcal{C}^B$	...	Set of beneficial criteria, denoted c
$\mathcal{C}^{NB}$	...	Set of non-beneficial criteria, denoted c

Parameters		
w_{dc}	...	Weight factor for criterion c by decision maker d
P_{adc}	...	Performance of criterion c for decision maker d for alternative a
N	...	Number of decision makers

Variables		
w_c	...	Average weight for criterion c
U_{adc}	...	Utility of criterion c for decision maker d in alternative a
U_{ac}	...	Average utility of criterion c in alternative a

Decision variable		
x_a	...	1 if alternative a is chosen, 0 else

Multi-objective optimization model formulation:

$$max \sum_{a \in A} \sum_{c \in C} x_a w_c U_{ac} \tag{4.1}$$

$$Subject\ to:$$

$$w_c = \sum_{d \in D} \frac{w_{dc}}{N}, \quad \forall c \in \mathcal{C}, \tag{4.2}$$

$$U_{acd} = \frac{P_{acd}}{max(P_{acd})}, \quad \forall a \in \mathcal{A}, \forall c \in \mathcal{C}^{NB}, \forall d \in \mathcal{D}, \tag{4.3}$$

$$U_{acd} = \frac{min(P_{acd})}{P_{acd}}, \quad \forall a \in \mathcal{A}, \forall c \in \mathcal{C}^{B}, \forall d \in \mathcal{D}, \tag{4.4}$$

$$U_{ac} = \sum_{d \in D} \frac{U_{acd}}{N}, \quad \forall a \in \mathcal{A}, \forall c \in \mathcal{C}, \tag{4.5}$$

$$\sum_{c \in C} w_c = 1, \tag{4.6}$$

$$\sum_{a \in A} x_a = 1, \tag{4.7}$$

$$x_a \in \{0, 1\}, \quad \forall a \in \mathcal{A} \tag{4.8}$$

The objective function (4.1) maximizes the utility U of the transport systems a with regards to a weight factor w for criterion c, and decides on which transport system that will be chosen. Constraint (4.2) calculates the average weight factors w for criterion c. Constraints (4.3) and (4.4) define the utility U for decision maker d within criterion c for alternative a, dependent on if the attribute is beneficial or non-beneficial. Constraint (4.5) calculates the average utility of criterion c for alternative a. Constraint (4.6) ensures that the sum of weights w is equal to 1. Constraint(4.7) ensures that only one alternative a is chosen, while constraint (4.8) includes the binary requirement.

4.2.1 Alternative model formulation

The multi-objective optimization model presented in Equation 4.1-4.8 chooses the optimal transport system based on weight factors and performance indicators averaged on the decision-makers. Another method for calculating the total scores of the transport systems is proposed in Equation 4.9-4.15.

$$max \sum_{a \in A} x_a S_a \tag{4.9}$$

$$Subject\ to:$$

$$U_{acd} = \frac{P_{acd}}{max(P_{acd})}, \quad \forall a \in \mathcal{A}, \forall c \in \mathcal{C}^{NB}, \forall d \in \mathcal{D}, \tag{4.10}$$

$$U_{acd} = \frac{min(P_{acd})}{P_{acd}}, \quad \forall a \in \mathcal{A}, \forall c \in \mathcal{C}^{B}, \forall d \in \mathcal{D}, \tag{4.11}$$

$$S_a = \sum_{c \in C} \sum_{d \in D} \frac{U_{acd} w_{dc}}{N}, \quad \forall a \in \mathcal{A}, \tag{4.12}$$

$$\sum_{c \in C} w_{dc} = 1, \quad \forall d \in \mathcal{D}, \tag{4.13}$$

$$\sum_{a \in A} x_a = 1, \tag{4.14}$$

$$x_a \in \{0, 1\}, \quad \forall a \in \mathcal{A} \tag{4.15}$$

In this model formulation constraint (4.2), (4.5) and (4.6) is substituted by constraint (4.12) and (4.13). The scores of each transport system are calculated separately from the original weight factors and utilities of the criteria for each transport system. The total scores of each alternative are then found as the average for the decision-makers.

The original multi-objective optimization model will be used further in this thesis to evaluate the potential of a waterborne transport system compared to a road-based system. A comparison of the original and the alternative MOO model will be provided in Chapter 11, with regards to the sensitivity and consistency of the obtained results.

4.3 Explanation of input needed for the multi-criteria decision model

This section contains information on the required input in the multi-criteria decision model. Numerical values needed for computational studies will be presented in Chapter 9.

Sets

A set of alternative transport systems, $\mathcal{A}$, and a set of relevant decision-makers, $\mathcal{D}$, for the alternative transport systems must be established. The decision-makers could either be potential users of the transport systems, people affected by the systems in terms of noise, construction work, etc., or groups of individuals with political influence in city logistics. Based on the alternative transport systems and the relevant decision-makers, a set of criteria, $\mathcal{C}$, has to be established. These are split into beneficial and non-beneficial criteria due to how they will be normalized. The criteria must be developed in the interest of the decision-makers, and it must be possible to quantify performances of the transport system within the defined criteria. Examples of such criteria are voyage duration, cost of transportation, cost of maintenance, emissions from the operation, investment costs, etc.

Parameters

The decision-makers must perform a pairwise comparison of criteria they find relevant, which will be used as input in the AHP method and result in the weight factors w. A quantitative performance, P, is required input for calculating the utility in each criterion for each alternative, possibly for each decision-maker if relevant. When calculating the utility of each alternative, the performance of each criterion will be normalized according to the following formulas:

$$X = \frac{x_{min}}{x} \tag{4.16}$$

$$X = \frac{x}{x_{max}} \tag{4.17}$$

For non-beneficial attributes, i.e., attributes in which minimum values are desired, Equation 4.16 is used for normalization. The latter, Equation 4.17, is used for beneficial attributes, i.e., attributes where maximum values are desired.

4.4 Optimization software

Gurobi Optimizer, a mathematical optimization solver, has been used for solving the multi-objective optimization problem. The solver was implemented in Spyder, a free and open-source scientific environment written in Python. The Gurobi Optimizer provides advanced implementations of the latest algorithms, including linear and mixed-integer programming. The Gurobi Optimizer can be used to develop mathematical optimization models and turn them into full-featured applications. The optimization software has also been used for computational studies of the multi-commodity vehicle routing model presented in the subsequent chapter.

Chapter 5

Multi-commodity vehicle routing optimization model

Approximately 80% of the world trade is carried by sea, making waterborne transport a significant mode of international trade. Ships involve major investments and high operating costs, and as discussed in Chapter 2, the industry is responsible for 13% of the total EU transport emissions. Thus, proper ship routing is vital in the shipping industry to reduce costs and emissions and increase competitiveness in the industry.

The multi-objective optimization model presented in Chapter 4 is a tool for helping decision-makers choose a mode of transport based on their preferences among a set of criteria and the performances of the alternatives within each criterion. One of the transport alternatives in this thesis is an urban water transport system consisting of modular vessels, where operational features must be established. Therefore, a binary multi-commodity vehicle routing optimization model has been created to find the optimal fleet size and routing and define operational characteristics of the waterborne transport system while minimizing annual expenditures.

5.1 Problem definition

Figure 5.1 illustrates a system of nodes representing different locations with various demands for cargo and passengers. The system is to represent an area similar to a fjord, where waterborne transportation can be used to transport commuting workers during peak commuting periods and distribute cargo outside these periods.

The system consists of a city center, a distribution center/fabrication facility, and a suburban area. The different locations are split into several nodes for the route generation process, explained in Chapter 9. Node 1, 2, and 3 represents a city center with a demand for passengers and cargo, node 7 represents a suburban area with a distribution center or a fabrication facility, and node 4, 5, and 6 represents a suburban area with a demand for passengers and cargo. The arrows represent the flows of the different commodities in the system.

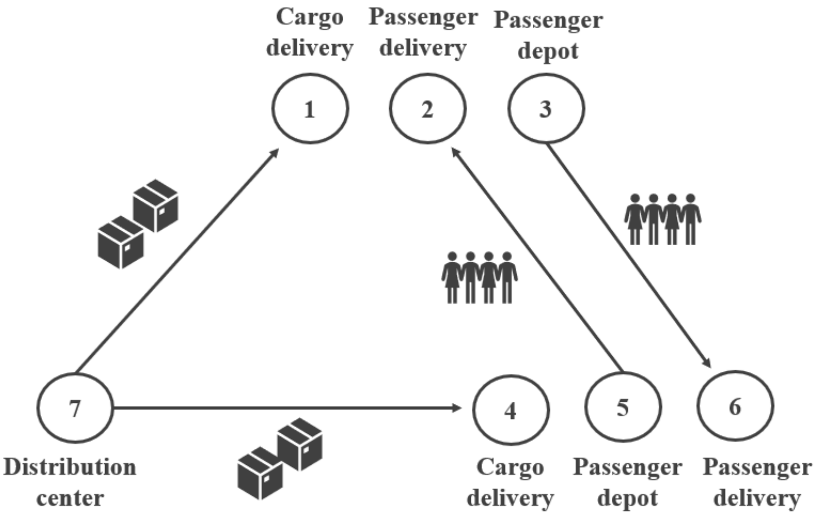


Figure 5.1: Illustration of a system where a waterborne transport system consisting of modular vessels could be fitting.

5.2 Multi-commodity vehicle routing model formulation

A multi-commodity vehicle routing model has been developed to find the optimal fleet size and routing for the defined problem definition. The optimization model uses pre-generated routes as input and belonging characteristics such as investment costs, operational expenditures, and the demand covered and starting times of each route. The model returns the combination of routes that fulfills the daily demand in the various nodes with as low as possible annual expenditures.

The following model notation and formulation, given in Equation 5.1-5.4, have been developed to solve the defined vehicle routing problem.

Multi-commodity vehicle routing model notation:

Sets

$\mathcal{N}$	...	Set of nodes, denoted i
$\mathcal{R}$	...	Set of feasible routes, denoted r
$\mathcal{C}$	...	Set of commodities vessels can transport, denoted c

Parameters

C_r^{DA}	...	Daily costs in route r
C_r^{EAC}	...	Equivalent annual cost of route r
T	...	Number of operating days per year
A_{ir}	...	Number of visits in node i when sailing route r
D_{ic}	...	Daily demand in node i of commodity c
K_c	...	Capacity of vessel when transporting commodity c
t_{ir}	...	Starting time of sailing from node i in route r

Decision variable

x_r	...	1 if route r is chosen, 0 else

Multi-commodity vehicle routing model formulation:

$$min \sum_{r \in R} x_r (C_r^{EAC} + C_r^{DA} T) \tag{5.1}$$

$$Subject\ to:$$

$$\sum_{r \in R} A_{ir} x_r = \sum_{c \in C} \frac{D_{ic}}{K_c}, \quad \forall i \in \mathcal{N}, \tag{5.2}$$

$$t_{ir} x_r \neq t_{i,r+n} x_{r+n}, \quad \forall i \in \mathcal{N}, \forall r \in \mathcal{R}, \tag{5.3}$$

$$x_r \in \{0, 1\}, \quad \forall r \in \mathcal{R} \tag{5.4}$$

The objective function (5.1) minimizes the total annual operational and capital expenditures for the fleet of vessels, i.e., sailing costs, port charges, cost of switching modules, equivalent annual investment costs, and operational expenditures related to maintenance and such. Constraint (5.2) ensures that the demand for commodity c in each node i is covered and that the vessel capacity is not exceeded. Constraint (5.3) ensures that each vessel does not leave the same node i at the same time in route r so that only one vessel is sailing one leg at a time. Constraint (5.4) includes the binary requirement.

5.3 Explanation of input needed for the multi-commodity vehicle routing model

This section contains information on the required input for solving the optimization model. Numerical values needed for computational studies will be presented in Chapter 9.

Sets

A set of commodities, $\mathcal{C}$, and feasible routes, $\mathcal{R}$, for transporting the commodities must be established. The routes can be generated manually or digitally using a feasible algorithm and relevant heuristics. All feasible routes should be used as input, or a subset of all routes, to find the optimal solution to the vehicle routing problem. The route generation process will be explained in more detail in Chapter 9. A set of nodes, $\mathcal{N}$, must be established, representing the various locations with demands for cargo and passengers.

Parameters

As the vehicle routing model aims to find the optimal fleet size and routing while minimizing annual expenditures, several cost parameters must be included to model the system properly. The daily cost for each route, C_r^{DA}, includes port charges, sailing costs, and the cost of switching modules. The sailing costs can be determined from the distances between the nodes, the speed of the vessels, and the required installed power. The port charges must be based on the charges in the ports in the locations the vessel will operate. The equivalent annual cost of each route, C_r^{EAC}, includes investment costs and operational costs related to maintenance and such of the vessels. The daily demand in each node can be found by investigating statistics from the relevant locations in the system. The vessels' capacity will be estimated from the defined main dimensions of the ship. The starting times of sailing from the nodes in each route can be calculated from the vessels' speeds and the distances between the locations.

Chapter 6

Methodology of life cycle assessment

There is a general need to support decision-making with complete and detailed information about the environmental impacts of products, services, and technologies. Life cycle assessment (LCA) is a method for assessing the overall environmental impact from the whole value chain of a product and a tool for attributing environmental impacts to products and services, enabling owners and operators to investigate impacts in a range of different categories.

Life cycle assessment (LCA) will be used for assessing the global warming potential (GWP) impacts of each transport system, which is one of the criteria in the multi-objective optimization model presented in Chapter 4 in which the transport systems will be compared. In this chapter, the methodology used for conducting LCAs will be presented, including the LCA software and the impact assessment methods used in this thesis.

6.1 Procedure for LCA

Life cycle assessment is generally described as a procedure with four steps, based on standards provided by the International Organisation for Standardisation (ISO) (Golsteijn 2022). The method for conducting an LCA is described by Figure 6.1. It is an iterative process requiring frequent evaluation and interpretation of each step of the process for the assessment results to fully comply with the goal and scope defined in step 1. The four steps of the LCA will be further explained in the subsequent sections.

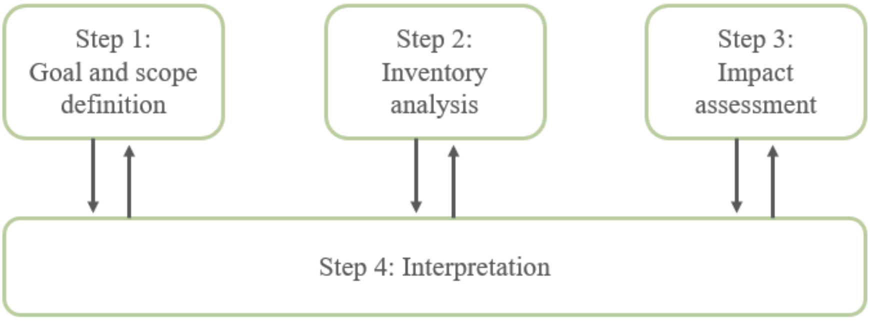


Figure 6.1: The procedure for conducting an LCA.

6.1.1 Goal and scope definition

It is important to carefully define the goal and scope of a life cycle assessment study to make sure that simplifications and distortions do not influence the results too much. Thus, goal and scope definitions ensure that an LCA is performed consistently (Golsteijn 2022).

The life cycle assessments carried out in this thesis will be conceptual LCAs, meaning that the assessments are based upon a limited and qualitative inventory. Thus, they are not complete assessments of the GWP impacts over the transport systems' whole lifecycles. All though, the preliminary assessments can be helpful for decision-makers to identify which strategies that have a competitive advantage in terms of reduced environmental impacts.

The LCAs will be "cradle-to-grave" assessments aiming to evaluate global warming potential impacts from all of the life phases of the urban water transport system and the road-based transportation system. The cradle-to-grave assessments will compile and examine the inputs of material and energy needed to construct the two transport systems. They will also represent the associated environmental impacts directly attributable to the systems throughout their life cycles. The aim of the LCAs is to quantify and compare the environmental impacts arising from the urban water transport system and a road-based transportation system.

The scope of the life cycle assessments is an investigation of GWP impacts arising from production, transportation of passengers and cargo over the transport system's lifetime, and end-of-life treatment of the vehicles in the transport systems. As the function of both the waterborne and road-based transport system is to transport passengers and cargo, the functional unit is defined as the transportation of one passenger and transportation of one TEU of cargo.

6.1.2 Inventory analysis

The definition of the goal and scope of the study provides the initial plan for conducting step 2 of an LCA, the Life Cycle Inventory (LCI) analysis. All environmental inputs and outputs associated with a product or service should be covered in the LCI. Inputs such as extraction and use of raw materials and energy must therefore be covered in addition to outputs such as emissions of pollutants from specific processes (Hauschild et al. 2015).

A preliminary systematic mapping of activities associated with production, operation, and end-of-life treatment of the systems must be performed. Flowcharts illustrating how background and foreground processes are connected and how they interact should be constructed for both systems. Foreground processes refer to data that is compiled specifically for a given study. Background processes refer to the generic database processes, such as materials needed to produce the vessel hull or fuel required for the operation of the road-based transport system. In this thesis the life cycle inventory database Ecoinvent 2.2 will be used.

6.1.3 Impact assessment

A life cycle impact assessment (LCIA) has the purpose of translating the elementary flows from the life cycle inventory into their potential contributions to the environmental impacts that are considered in the LCAs. LCIA aims to support the interpretation phase where the questions posed in the goal definition are answered (Hauschild et al. 2015).

According to ISO standards, LCIA consists of five steps. In step 1, the impact categories are selected in accordance with the goal of the study. In step 2, the elementary flows of the inventory are assigned to relevant impact categories among those selected in step 1. In step 3, each amount of each elementary flow assigned to an impact category is multiplied with a so-called characterization factor, which is a quantitative representation of an elementary flow's importance for a specific impact category. The resulting indicator score is given in kg stressor-equivalents, dependent on the impact category. For example, the indicator score for GWP impacts is given in kg CO_2-equivalents. The total impact score within each category is the sum of all the indicator scores for all the elementary flows contributing to that specific category (Hauschild et al. 2015). The impacts scores are called midpoint indicators, which are the focus area in this thesis. The optional steps 4 and 5 aim to translate these midpoint indicators into endpoint indicators showing the environmental impacts on higher aggregation levels. In this thesis, steps 4 and 5 will not be carried out.

6.1.4 Interpretation

Step 4 in the procedure for conducting an LCA includes an interpretation of both the inventory analysis and the impact results. The interpretation should include an identification of significant contribution impacts from stressors and activities based on the results of the LCI and LCIA. It should also include an evaluation that considers completeness, sensitivity, and consistency checks, in addition to conclusions, limitations, and recommendations (Hauschild et al. 2015). Sensitivity and consistency checks will not be performed since the LCAs to be conducted in this thesis are based upon simplified life cycle inventories.

6.2 LCA software

The LCA software program Arda will be used for conducting the life cycle assessments. The program uses the impact assessment method ReCiPe with a hierarchist midpoint method to transform life cycle inventory results into a limited number of indicator scores within different impact categories. Arda is assisted by the software programs Excel and MATLAB. Excel is used to generate the foreground and background system, which will be used as input in MATLAB, where Arda is used for performing the impact assessment. The results from Arda will then be uploaded to Excel for interpretation.

Chapter 7

Case study: Fjord of Oslo

Urbanization has led to an increasing population and relocation of workplaces into the main city of Oslo. As a result, the population has increased by over 50 000 residents since 2015, and at the beginning of 2021, over 4000 new businesses in the city were registered (Oslo Kommune 2022). Oslo is thus heavily affected by working commuters and cargo importation, which will continue increasing in the years to come. Therefore, the development of climate-friendly and efficient transport systems will be crucial for handling the large movements of freight and passengers in the city.

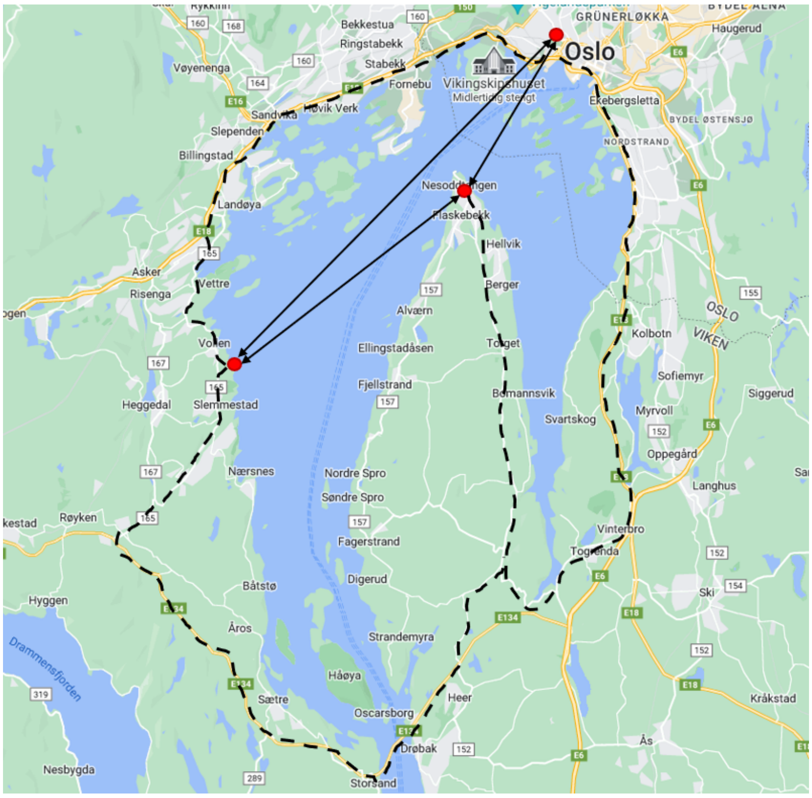


Figure 7.1: Illustration of the case study in the fjord of Oslo.

The fjord of Oslo has been chosen for the case study due to its geographical features, in addition to the relevant influence of commuters into the central city and the large flows of cargo imported from nearby communes and regions. Figure 7.1 illustrates the case study, where passengers and cargo are to be transported between three locations; The main city of Oslo, the suburban area Slemmestad, and the suburban area Nesodden. The broken lines illustrate the paths for road transportation, and the solid lines the paths for waterborne transportation. The daily demand and supply of passengers and cargo defined in each location aim to represent the situation in the areas today.

A waterborne transport system consisting of modular vessels alternately transporting passengers and cargo will be compared to road-based transport by private cars and trucks to evaluate performances within voyage duration, environmental impacts, and costs related to means of transportation. The case study is performed to evaluate the performances of a waterborne transport system with compared to a road-based transport system. This chapter provides information on urban mobility in Oslo, the daily demand for passengers and cargo in the various locations, and the operational features of the locations under investigation.

7.1 Urban mobility in Oslo

7.1.1 Commuting activity

As discussed in Chapter 2, approximately 88 000 people were registered as commuting workers into Oslo from the ten largest contributing communes; several of them located near water. Statistics also show that the amount of commuters has increased by approximately 13% from 2010 to 2017 (Kommuneprofilen 2022). Nesodden, a commune in the Oslo region, is among these communes. Almost 5000 people were registered as commuters in 2017, i.e., approximately 25% of the residents in the commune. The population density in Nesodden is highest in the North, nearest to the city of Oslo. Today, a ferry service provides crossings between Nesodden and Aker Brygge, with frequent departures in the morning and late afternoon when commuting activity is at its highest. The ferry service is eagerly used by the commuting workers in the commune, as traveling by road involves a much longer voyage duration.

7.1.2 Importation of goods

As discussed in Chapter 2, the incoming and outbound domestic cargo volumes through the port of Oslo are relatively low. But, Oslo imports millions of tonnes of cargo each year by road freight. Statistics from 2019 show that almost 0,9 million tonnes of goods were transported by road freight to Oslo from regions northwest of Slemmestad, such as Vestfold, Telemark, and Agder. The amount of cargo equals a daily distribution of approximately 2500 tonnes. A multimodal transport network could thus be suiting, as road freight could be substituted by waterborne transport in Slemmestad and transported by sea to the city of Oslo. Assuming a TEU can carry approximately 25 tonnes of dry goods, the daily rate of transported cargo into Oslo from the mentioned locations will be about 100 TEUs.

7.2 Explanation of case study

In the case study of this thesis, two alternative transport systems will be compared with regard to a set of criteria and the preferences among the criteria for relevant decision-makers. The transport alternatives will be a waterborne transport system consisting of modular vessels alternately transporting cargo and passengers and a road-based transport system consisting of ICEVs, EVs, and conventional trucks. The decision-makers are a commuter and a cargo owner, and the criteria are listed in Table 7.1. The performance of the transportation alternatives will be be quantified in each criterion, for each decision-maker. The listed criteria are all non-beneficial attributes, i.e., attributes in which minimum values are desired.

Table 7.1: The criteria relevant for which transport system the decision-makers will use.

Criterion no.	Type of criteria	Unit
1	Global warming potential	kg CO_2-eq
2	Voyage duration	h/voyage
3	Lead time	h/voyage
4	Cost of transportation	NOK/trip

The global warming potential will be found by performing life cycle assessments of both transport systems by using the methodology described in Chapter 6. The transport alternatives will then be compared with regards to their GWP impact per passenger transported and per TEU of cargo transported between the locations. Voyage duration, potential lead time, and cost of transportation will be calculated according to cost coefficients and parameters presented in Chapter 9.

Table 7.2 presents the daily demand and supply of passengers and cargo in the suburban areas Slemmestad and Nesodden and the center of Oslo. The daily demand and supply of freight are based on the statistics from 2019 presented in Section 7.1. Slemmestad has a supply of 100 TEUs of cargo, which is a large share of the cargo transported initially by road from locations that will pass the commune into Oslo. In addition, a total of 20 TEUs are to be transported to Nesodden to further explore the potential effects of the waterborne transport system.

Table 7.2: The daily demand for passengers and cargo in the locations Oslo, Nesodden, and Slemmestad.

Location	Node i	Daily demand in node i	Daily supply in node i	Unit
Oslo	1	80	-	TEU
Oslo	2	2100	-	PAX
Oslo	3	-	2100	PAX
Nesodden	4	20	-	TEU
Nesodden	5	-	2100	PAX
Nesodden	6	2100	-	PAX
Slemmestad	7	-	100	TEU

Table 7.3 represents the schedule for departures and arrivals from the suburban area Nesodden to Oslo, more precisely Aker Brygge, and vice versa. The schedule is based on the number of commuters Oslo experienced from the nearby commune in 2017 and adapted to the expected number of commuters based on the geographical features of Nesodden. The schedule for the urban water transport system is also inspired by the already existing ferry service but is limited to departures only in peak commuting periods. Therefore, the modular waterborne transport service will offer seven crossings in the morning and the afternoon, with a frequency of departures every 20 minutes.

Table 7.3: The time schedule for pickup and delivery of passengers between Oslo and the suburban are Nesodden.

Morning		Afternoon	
Departure	Arrival	Departure	Arrival
0600	0620	1500	1520
0620	0640	1520	1540
0640	0700	1540	1600
0700	0720	1600	1620
0720	0740	1620	1650
0740	0800	1640	1700
0800	0820	1700	1720

It is assumed that cargo can be transported anytime outside the commuting periods, daytime and night. Therefore, the demand defined in Table 7.2 is given as a daily demand, and no node, or location, requires the demand to be fulfilled at specific times.

Table 7.4 present the distances between the locations Nesodden, Oslo, and Slemmestad by sea. The distances are given in nautical miles (nm).

Table 7.4: The distances by waterborne transportation between the locations Nesodden, Oslo and Slemmestad.

From-To	Distances	Unit
Nesodden-Oslo	3.4	nm
Slemmestad-Oslo	10.6	nm
Nesodden-Slemmestad	8.3	nm

7.2.1 Definition of the road-based transport system

Based on the daily demand and supply of passengers and cargo presented in Table 7.2 and the distances between the locations in the system by road given in Table 7.5, a road-based transport system has been defined. The system shall cover the daily demand for passengers and cargo as the urban water transport system. All commuters are assumed to travel by private vehicles where half of these vehicles will be ICEVs, with the other half being EVs. The average car occupancy is set to 1.5 persons per vehicle. Based on the daily demand and supply of passengers in Oslo and the suburban area of Nesodden, 700 cars of each type are needed.

Cargo is assumed to be transported by freight trucks carrying one TEU each. Cargo handling duration is set to 15 minutes, and the distances of each voyage are defined in Table 7.5. The trucks will be able to travel by night, like the modular vessels in the waterborne transport system. Based on these parameters, five trucks are required for fulfilling the daily demand for cargo in Oslo and Nesodden, with each truck transporting a total of 20 TEUs in one day. Thus, each truck will have to execute 20 roundtrips each per day.

Table 7.5: The distances by road transportation between the locations Nesodden, Oslo and Slemmestad.

From-To	Distances	Unit
Nesodden-Oslo	46	km
Slemmestad-Oslo	31	km
Nesodden-Slemmestad	50	km

7.3 Comments and notes on the case study

This case study is relevant for exploring the potential benefits of implementing an urban water transport system consisting of modular vessels compared to a road-based transport system. The fjord of Oslo is used as a base case, and the numbers and values used for defining the daily demand and supply of cargo and passengers may differ from the real-life situation. Additionally, the ports in Nesodden, Oslo, and Slemmestad are assumed to have the equipment required for the operation of the modular vessels, such as cranes for cargo handling and attaching and detaching modules in addition to necessary energy supply systems for powering the modular ships. Thus, these concerns are not considered in this thesis, nor costs related to development and maintenance of ports and equipment.

Chapter 8

Description of vessel concept

One of the main objectives of this thesis is to investigate the potential of modular vessels alternately transporting passengers and cargo by using modularization technology. A review of the use of modularity in ship design was presented in Chapter 3, where its application in the maritime industry was found to be somewhat limited.

This chapter discusses the configuration of the modular vessels and what kind of technology is required for enabling transitions between ”passenger mode” and ”cargo mode”. The main dimensions, hull structure, and load capacity of the modular vessels have been defined based on the daily demand for passengers and cargo presented in Chapter 7. Further, the chapter elaborates on sailing speeds, and the corresponding installed power in both vessel modes and provides a discussion of battery-electric propulsion in short-sea shipping and the potential for autonomous operation of the vessels.

8.1 Design considerations

8.1.1 Configuration of modular vessels

The modular vessels must be able to operate and switch between two vessel configurations in a short period of time. Thus, the use of standardized modules has been proposed. When the vessel is required to transport passengers, a passenger module will be lifted onto and installed on the vessel’s main deck. Passengers will be allowed to enter the ship after the passenger module is attached. When transporting cargo, this passenger module will be detached and loaded TEUs will be placed directly onto the main deck, which can be fitted into standardized container slots. Thus, this configuration method uses a lift-on/lift-off (LoLo) approach. The vessels will have a bus-modular architecture, where there is one standard part to which the other modules connect via the same type of interface. The passenger module is assumed to be attached and detached by using the same cranes that load and unload cargo. Each transition between the two configurations is expected to take 1 hour.

Another proposed method is to use a roll-on/roll-off (RoRo) approach. The main deck of the modular vessels could be lowered or raised through ballasting, depending on the tide, to the same level as the port. The passenger module could be considered a large container that passengers already have entered, and through the use of a roll-on/roll-off approach, the module could be rolled onto the main deck by wheeled handling equipment and put in place. However, loading and unloading of TEUs could be challenging as the containers most probably will have to be stacked in height. Thus, a hybrid method combining RoRo and LoLo approaches might be necessary.

The latter method could potentially reduce the duration of each configuration from "cargo mode" to "passenger mode." However, it would require a more extensive shore system and more advanced technology to enable the concept. Thus, this thesis will look into the LoLo method for configuration of the modular vessels

8.1.2 Hull structure and main dimensions

As the modular vessels are to transport commuting workers, the voyage duration must be competitive with the alternative of using private cars or public road transportation services. For the case study in this thesis, the distances when traveling by road is considerably longer than when traveling by sea between Oslo and Nesodden, and Slemmestad and Nesodden. This situation may not be for other areas where waterborne transport could be implemented. Thus it is desirable to aspire for higher vessel speeds when transporting passengers. Speeds over 12 knots are difficult to achieve for traditional monohull designs. Thus twin-hull structures will be preferable for the modular vessels. To decrease the resistance when transporting passengers and thus obtain high speeds, the passenger module could be built in aluminum which is considerably lighter than steel.

Based on the defined demand and supply of cargo and passengers and the schedule for passenger departures presented in Chapter 7, the main dimensions and load capacity presented in Table 8.1 are defined for the modular vessel. Cargo can not be stored under the main deck due to the structure of the hull. Cargo will thus be stored in TEUs on the main deck, stacked in height. A passenger module will be lifted onto and installed on the main deck when transporting passengers, using the LoLo approach discussed in the former section. 300 passengers could be seated over two floors in the passenger module while still providing enough space for a wheelhouse and to store batteries on deck, assuming an area coefficient of 1.5 m^2 per passenger.

Table 8.1: Main dimensions and load capacity for modular vessels.

Length over all	**Beam over all**	**Load capacity, passengers**	**Load capacity, cargo**
45 m	12 m	300 PAX	20 TEU

8.1.3 Speed and power requirements

As discussed in Subsection 8.1.2 it is desirable with high speeds when transporting passengers to be competitive with road-based transportation. The schedule proposed for pickup and delivery of passengers between Oslo and Nesodden requires a crossing duration of 15 minutes, which will result in a crossing speed of approximately 14 knots. Figure 8.1 illustrates the relationship between the required installed power and the overall length for twin-hull vessels (Ormevik 2020). The power requirement for a ship with an overall length of 45 m will be approximately 1700 kW if sailing at 14 knots.

The modular vessel will be significantly heavier when transporting cargo, resulting in high voyage costs when sailing at high speeds. As discussed in Chapter 7, the daily demand for goods can be fulfilled at any time of the day. This flexibility allows for a reduction in the sailing speed of the modular vessel when transporting cargo, which is beneficial for the energy consumption of the vessels and the resulting sailing cost. The speed is thus set to 10 knots when transporting cargo from Slemmestad to Oslo and Nesodden. From Figure 8.1 the power requirement for vessels with an overall length of 45 m sailing at 10 knots is approximately 1200 kW. A summary of power requirements and average speeds for the modular vessel can be seen in table Table 8.2.

Table 8.2: Average speeds and required power when sailing between the locations with various commodity.

Sailing leg	**Commodity**	**Average speed**	**Power req.**
Nesodden - Aker Brygge	Passengers	14 kn	1700 kW
Slemmestad - Aker Brygge	Cargo	10 kn	1200 kW
Slemmestad - Nesodden	Cargo	10 kn	1200 kW

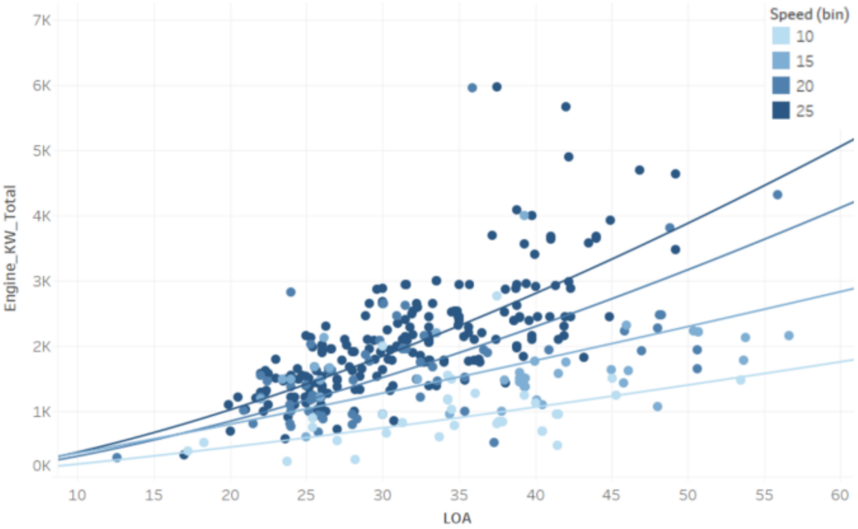


Figure 8.1: The relationship between required installed power and the overall length for twin-hull vessels (Ormevik 2020).

One of the main motivations for developing and implementing waterborne transportation in urban areas is to provide an environmentally friendly alternative to domestic cargo transportation by trucks and the use of private cars for passenger transport. Low-carbon solutions for propulsion will thus be essential for waterborne transportation to be competitive in terms of environmental impacts. Batteries can enable vessels to sail in zero-emissions mode, given that they are the only source of electricity, which will limit greenhouse gas emissions. Battery power can also allow for performing operations such as peak shaving and load leveling, which helps optimize energy consumption and allows for even more effective vessel performance. Use of battery electric propulsion can also contribute to reduced maintenance costs as batteries do not vibrate and move and will thus not require comprehensive maintenance as conventional marine engines do (Corvus Energy 2022).

Running a ship on batteries does come with environmental benefits and several operational benefits. Transportation of passengers will set higher requirements to comfort on board. Battery propulsion can ensure a smoother and quieter experience of waterborne transportation, which is essential when establishing a water transport system as a better alternative to usage of private cars. Low noise can also enable operation at night as the disturbing element is eliminated.

The modular vessels in the fleet will operate similar to a regular ferry, covering short, fixed routes and having regular docking in fixed locations. The batteries stored on the main deck can be charged when loading and unloading both passengers and cargo in the ports by using shoreline charging infrastructure. Several solutions for battery-powered vessels exist, distinguishing between conductive and inductive charging. Conductive charging uses direct contact between the ship and the inlet, while inductive charging uses an electromagnetic field to transfer energy between the vessel and the charging outlet. The latter enables power transfer to begin when the vessel is docked, which is beneficial as battery-powered vessels require as much docking time as possible for charging. Problems related to potential delays when performing manual connections can also be avoided, which is important when transporting passengers as the departures are scheduled (Wärtsilä 2022). For a fleet consisting of modular vessels, the attachment and detachment processes can be used as an advantage. As these processes will require a higher turnaround time, the extra time in port can be utilized for charging the batteries.

The required size of the battery packs is found from the installed power of the main engines. As the required power varies depending on what kind of commodity the vessels are transporting, it could be beneficial to have mobile battery packs which can be customized according to what is being transported. When transporting passengers, the vessels must be able to operate for approximately 2.5 hours, resulting in a consumption of 4250 kWh. When transporting cargo, the longest possible sailing leg is approximately 12 hours, resulting in a consumption of 14 400 kWh. As battery packs are expensive and require large areas for storage, solutions for fast charging will be explored. A battery pack of 3000 kWh combined with a charger with an effect of 3 MW will enable the modular vessels to cover one of the passenger periods and sail to Slemmestad for detaching the module. The configuration is estimated to take 1 hour, making it possible for the modular vessel to fully recharge and sail the longest voyage for transporting cargo.

8.2 Autonomous operation

The main motivation behind evaluating autonomous operation of the modular vessel is the need to create a robust and effective waterborne transportation system to be competitive with road-based transportation. The goal implies a need for more, and smaller, vessels that can substitute both domestically and abroad road transportation by enabling delivery to the cargo's final destination. For this to be economically viable, automation will be crucial. A transition from large ships to smaller transport units will require more labor at sea, and crew costs make up a significant part of the operational expenditures for smaller vessels. Automation of processes will increasingly allow for redeployment of labor from sea to land and can contribute to reducing costs related to accommodation for crew (NFAS 2018). Reduction in crew may also facilitate increased cargo capacity on board vessels, potentially contributing to improved energy efficiency and performance.

Another motivation for evaluating autonomous operation is to increase safety at sea. According to the European Maritime Safety Agency (2020), over 50% of the analyzed accident events in 2020 were due to human action involving personnel and manning. Moreover, nearly 90% of the victims in these accidents were crew members. By redeploying labor from the sea to land, the human factor in maritime shipping and operations and the number of people at risk at sea will be limited. It is thus interesting to investigate to what extent autonomy could be applied to the functions of the urban water transport system.

8.2.1 Alternative concepts

Initially, autonomy has been considered for cargo ships, as ethical questions arise when discussing autonomous transportation of humans. Autonomy does not necessarily imply fully unmanned vessels. IMO recognizes four degrees of autonomy (IMO 2021).

1. Ship with automated processes and decision support. Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and unsupervised, but seafarers are available to take control if necessary.
2. Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available to take control and operate the shipboard systems and functions if necessary.
3. Remotely controlled ship without seafarers on board. The ship is controlled and operated from another location.
4. Fully autonomous ship. The ship's operating system can make decisions and determine actions on its own.

As the modular vessels will alternately transport passengers and cargo, it is not justifiable to operate with fully autonomous ships. Personnel should be present in case of emergencies to guide passengers to safety or provide service to passengers with various disabilities. But, in periods when only cargo is transported, the vessels could potentially be unmanned. Thus, remotely controlled vessels with seafarers on board during certain periods could be a suitable alternative for the urban water transport system. Furthermore, transporting cargo with fully unmanned vessels could significantly reduce operational expenditures as the crew is not needed on board the vessels during these operations.

According to the Norwegian Maritime Authority (2019), the minimum crew requirement for a ferry with a capacity of 300 PAX is six persons. The same crew size is assumed to be required when operating in cargo mode. Based on statistics of salary (2022b), the annual crew cost for the defined modular vessel will thus be approximately 12.1 MNOK, assuming the crew consists of a master, a 1st mate, and four seamen, and that two shift of crew is required per day per vessel. If the fleet of modular vessels were to be remotely controlled vessels with seafarers on board only when operating in ”passenger mode,” it could potentially be sufficient with only one captain monitoring the vessel crossings and one seaman servicing the passengers. The annual crew costs could then be reduced by approximately 7.8 MNOK per vessel.

Chapter 9

Required input for computational studies

The required input for conducting computational studies of the models and approaches presented throughout this thesis will be provided in this chapter. The input required for the various models and methods is presented in chronological order, starting with route- and vessel-specific features needed to find the optimal fleet size and routing for the waterborne transport system. Then, the processes included in the life cycle assessments for assessing the global warming potential impacts from each transport system are presented and illustrated through flowcharts. Lastly, the parameters and coefficients for calculating the required input for the multi-objective optimization model are provided.

The chapter focuses on approaches and coefficients used for finding the final input parameters. An overview of the final input parameters used for computational studies can be found in Appendix A, Appendix B, and Appendix C.

9.1 Multi-commodity vehicle routing problem

9.1.1 Route generation process

The developed fleet scheduling model uses generated routes as input to find the optimal fleet size and routing solution for the defined case study. The routes have been generated using a multi-trip algorithm that combines single routes into multiple routes. The following constraints have been taken into consideration when generating the routes:

1. Each route shall have a maximum duration of 24 hours and shall end in the same area as where it started.
2. Scheduled passenger transportation periods must be covered, one in the morning and one in the afternoon. Each route must cover minimum one of the passenger transportation periods.
3. Transportation of passengers can only happen in the scheduled passenger periods, while cargo transportation can happen during daytime and at night.
4. At each route, no vessel shall carry more than its design load.
5. In each route, the vessel will have to switch between segments.

Fagerholt's approach for combining single routes into multiple routes has been used for generating the routes used as input in the developed path-flow model. The developed algorithm for combining single routes into multiple routes is inspired by an algorithm developed by Fagerholt (1999), with a few alterations to consider the constraints defined above.

Step 1: Generation of single routes

In the first step of the approach, single routes have been generated. Each scheduled passenger period is considered as one route, resulting in four obligatory routes for transportation of passengers as shown in Table 9.1.

Table 9.1: Scheduled passenger single routes.

Route r	**Start**	**Path**	**Demand covered**	**Duration**
R1	06.00	5-2-5-2-5-2-5-2	1200 PAX	2.37 h
R2	06.20	5-2-5-2-5-2	900 PAX	2.05 h
R3	15.00	3-6-3-6-3-6-3-6	1200 PAX	2.37 h
R4	15.20	3-6-3-6-3-6	900 PAX	2.05 h

The single routes for cargo transportation have been developed so that all possible combinations of vessel configurations are included. For example, a vessel can sail from any passenger node to the distribution center in node 7, cover an amount of the daily demand in either node 1 or node 4, and then sail back to any other passenger node. Examples of these routes can be seen in Table 9.2.

Table 9.2: Examples of single routes for transportation of cargo, including necessary vessel configurations for switching between passenger mode and cargo mode.

Path	Demand covered	Duration
2-7-4-7-3	20 TEUs	7.12 h
7-4-7-3	20 TEUs	5.36 h
6-7-1-7-1-7-5	40 TEUs	11.38 h
2-7-1-7-1-7-1-7-4-7-5	80 TEUs	19.29 h

The multiple trips, or routes, are already introduced in the scheduled passenger routes and the routes for cargo transportation. Therefore, in this route generation process, the multiple routes generated in step 2 are defined as the number of times a vessel undergoes a configuration from passenger mode to cargo mode and vice versa.

Step 2: Generation of multiple routes

Algorithm 1 presents a pseudo-code for the combination of the generated single routes into multiple routes. Let $\mathcal{R}_n$ be the set of all feasible n-routes, indexed by r, and let M_n be the number of n-routes in the set $\mathcal{R}_n$. Let $\mathcal{N}$ be the set of nodes, and $\mathcal{L}$ the set of locations. Let $\mathcal{C}$ be the set of commodities, and let D_{ic} be the demand in node i. DC_{irc} is the demand covered in node i in route r. t_r is the voyage duration of route r, T^{Max} is the maximal duration of the n-routes, and L_r^S and L_r^E is the starting location and ending location for route r, respectively.

Algorithm 1 Combination of single routes into multiple routes

```
$n = 1$
repeat
    for $j = 1$ to $M_1$ do
        for $k = 1$ to $M_n$ do
            if $[(t_{r_j \in R_1} + t_{r_k \in R_n} \leq T^{Max})$ and $(DC_{i,r_k \in R_n,1} = D_{i1}, \forall i)$ and
            $(\sum_{i \in I} DC_{i,r_k \in R_n,2} \geq 1)$ and $(DC_{i,r_j \in R_1,c} + DC_{i,r_k \in R_n,c} \leq D_{ic}, \forall i)$
            and $(L^S_{r_j \in R_1} = L^E_{r_k \in R_n})]$ then
                combine route $r_j \in R_1$ and $r_k \in R_n$ into new multiple route
                $r^* \in R_{n+1}$; calculate the cost of route $r^*$; calculate the demand
                covered in route $r^*$; calculate voyage duration in route $r^*$; update
                the starting location and ending location of route $r^*$;
            end if
        end for
    end for
    $n = n + 1$
until no new combined multiple routes can be generated;
```

By following the steps in Algorithm 1, a total of 55 routes were generated. The generated routes are a combination of multiple routes, with 24 2-routes, 29 3-routes, and 2 4-routes. In each route, the modular vessel switches segments at least once and at most four times. No route exceeds the maximum allowed duration and the daily demand for passengers and cargo in the various locations.

9.1.2 Investment costs and operational expenditures

The equivalent annual cost of choosing route r can be found by using the following equation:

$$EAC = \frac{C^{INV}}{1-(1+r)^{-n}} r + C^{OP}, \tag{9.1}$$

where C^{INV} is the investment cost of the modular vessel, C^{OP} is the operational expenditures, r is the annual interest rate, and n is the lifetime of the ship. The annual interest rate is set to 5%, and the lifetime of the modular vessels is assumed to be 25 years. The investment costs of the modular vessel are calculated according to Figure 9.1 and by using the cost coefficients listed in Table 9.3.

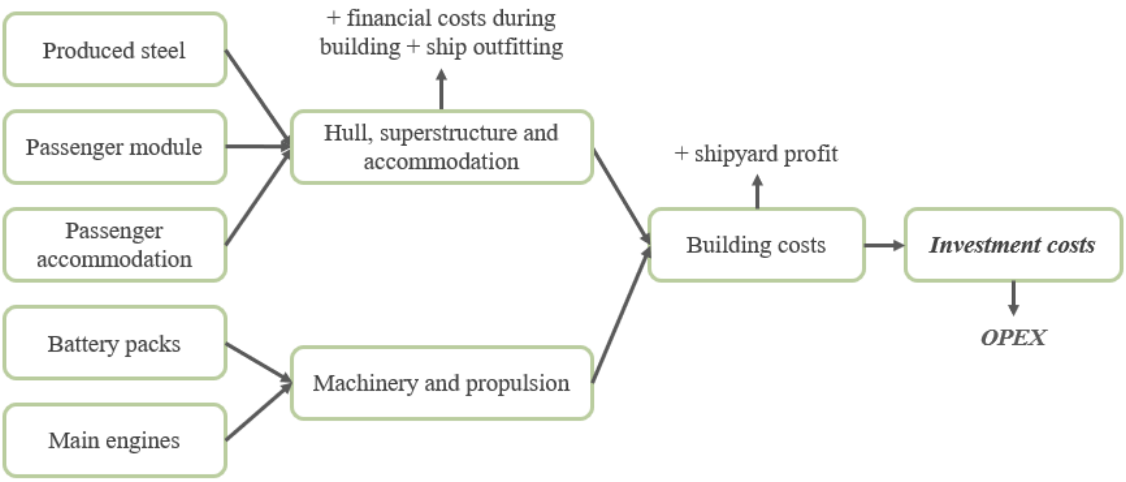


Figure 9.1: Illustration of cost components included in the calculation of investment costs and operational expenditures for the modular vessels.

Table 9.3: Cost components and coefficients used for calculating the investment costs of the modular vessels (Ormevik 2020; Amdahl et al. 2015).

Cost component	**Coefficient**	**Unit**
Produced steel	35 000	NOK/tonnes
Passenger module	80 000	NOK/m^2
Passenger accommodation	20 000	NOK/m^2
Battery packs	12 000	NOK/kWh
Main engines	4000	NOK/kW

The financial costs of building and ship outfitting are assumed to be 5% and 10% of the hull and superstructure costs, respectively. The shipyard profit is assumed to be 10% of the total building costs, and the annual operational expenditures are assumed to be 4,5% of the total investment costs (Amdahl et al. 2015). These coefficients and parameters will result in an investment cost of 140 MNOK and an annual operational expenditure of 6.3 MNOK per vessel.

9.1.3 Voyage costs

The sailing costs for the modular vessels can be calculated from the energy consumption per crossing by using the following formula:

$$C_r = P * t * C^E \tag{9.2}$$

where P is the power requirement, t is the sailing duration of each route, and C^E is the price of electricity in the ports. The power requirement and speeds and distances for the vessels between each location can be found in Table 7.4 and Table 8.2. The price of electricity for charging batteries in the ports is assumed to be 1,7 NOK/kWh, based on the average price of electricity in 2022. Manning costs are neglected in the calculation of the voyage costs.

9.1.4 Port charges and cargo handling costs

The charges in the Port of Oslo are used for estimating port charges and cargo handling costs for the port of Aker Brygge, Nesodden, and Slemmestad. The charges are assumed to be the same for all ports in the system, and the parameters used for calculating the port charges and cargo handling costs of the diverse routes are given in Table 9.4.

Table 9.4: Cost coefficients needed for calculating port charges and cargo handling costs for the routes used as input in the vehicle routing optimization model (Oslo Havn KF 2022).

Cost component	Coefficient	Unit
Port charges	200	NOK/m per month
Cargo handling	186	NOK/TEU

9.2 Life cycle assessment

The global warming potential impacts, measured in kg CO_2-equivalents per passenger and per TEU transported, have been found by conducting life cycle assessments of the defined urban water transport system with modular vessels and the road-based transport system consisting of ICEVs, EVs, and conventional trucks. Only the major contributing processes to GWP impacts have been included in the assessments. These processes have been found by investigating LCAs of electric ferries, conventional and electric cars, and trucks, presented in the literature study in Chapter 3.

9.2.1 Life cycle assessment of electric modular vessels

The description of the main dimensions and structure of the hull and passenger module presented in Chapter 8, in addition to the input used in the LCAs conducted by Ringström (2019) and Galaaen (2020), has been used to define the input parameters required for conducting the LCA of the waterborne transport system.

A flowchart representing the flows between the foreground processes in the urban water transport system consisting of modular vessels can be seen in Figure 9.2. The primary materials needed for constructing the vessel hull and the passenger module in the production phase include steel, aluminum, and copper. When assembling the vessel, electricity will be needed. It is unknown where the vessel will be built, so a European production mix is assumed. During operation, the ship is assumed to be powered on a Norwegian supply mix, and electricity consumption due to distribution and transmissions are also included. The end-of-life treatment of the vessel will also require electricity, which is assumed to be a European production mix due to the same reasons as the vessel's assembly.

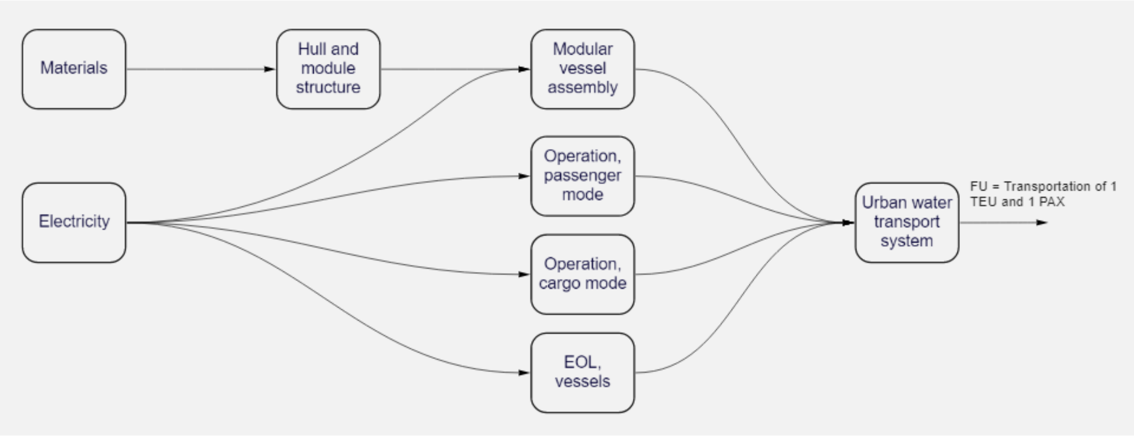


Figure 9.2: Flowchart representing the foreground processes in the waterborne transport system.

A more detailed description of input parameters included in the life cycle inventory of the urban water transport system can be found in Appendix A.

9.2.2 Life cycle assessment of private vehicles and trucks

The road-based transport system consists of ICEVs, EVs, and conventional trucks, and all vehicles have to be assessed with regards to GWP impacts to find the total impact of the road-based transport system. The description of the road-based transport system provided in Chapter 7, in addition to raw data provided in the course TEP4223 Life Cycle Assessment of emissions related to ICEVs and EVs, has been used to define the input parameters needed for conducting the LCA of the road-based transport system.

A flowchart representing the flows between the foreground processes in the road-based transport system can be seen in Figure 9.3. The primary materials needed for constructing the main body of the cars and the trucks include steel, copper, iron, and zinc. As for the modular vessels, a European production mix is used for assembling the vehicles. The operation of the ICEVs and the trucks will require diesel, and the EVs are assumed to be powered on a Norwegian supply mix. The end-of-life treatment of the trucks and the private vehicles also requires electricity, which is a European production mix for the same reasons as the modular vessels. It has been assumed that the materials required for production and the energy consumption for assembly and end-of-life treatment for private cars yield for trucks, and they have thus been scaled up to fit the size of the defined trucks.

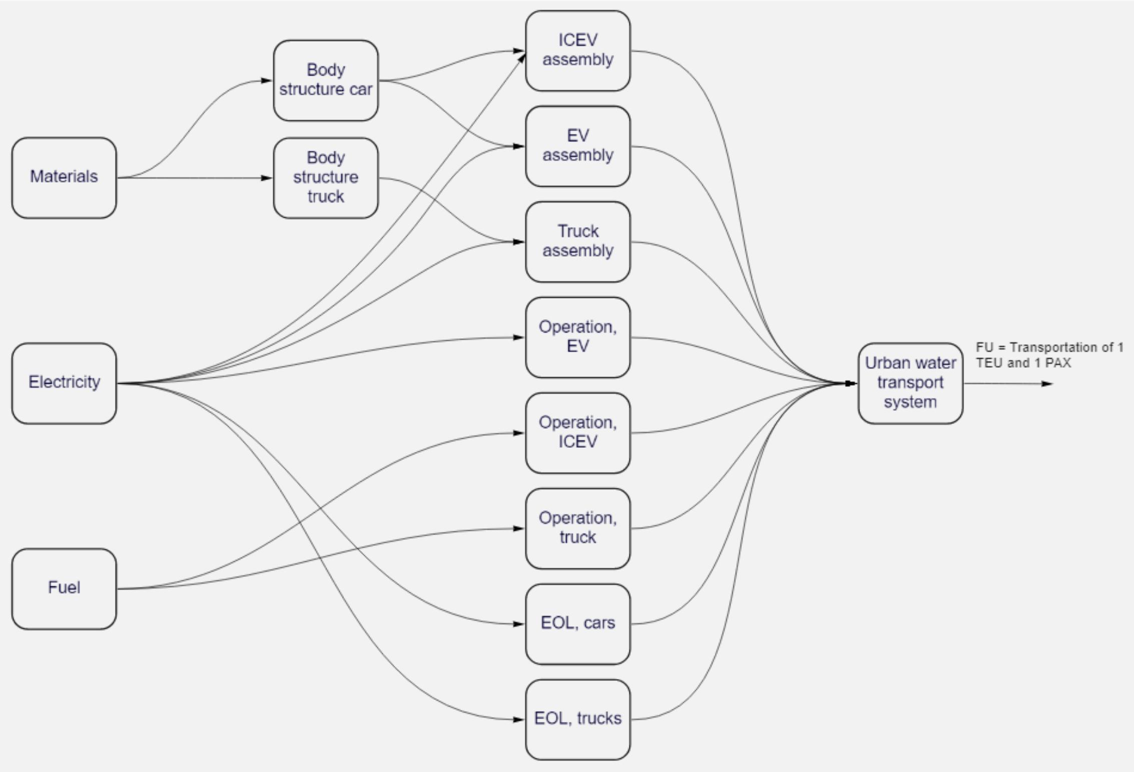


Figure 9.3: Flowchart representing the foreground processes in the road-based transport system.

A more detailed description of input parameters included in the life cycle inventory of the road-based transport system can be found in Appendix B.

9.3 Multi-objective optimization model

As stated in Chapter 7, there will be two different decision-makers; Commuting workers and cargo owners. The transport systems will be compared with regard to four criteria; GWP impacts, voyage duration, potential lead time, and cost of transportation, which are chosen in relevance for the decision-makers. This section elaborates on the required input in the multi-objective optimization model. It provides information on how the performances of the transport systems in the remaining criteria are found, in addition to how the weight factors are found from the AHP method.

9.3.1 Voyage duration and potential lead time

The voyage duration is calculated from the distances between the locations in the case study and the service speeds of the vehicles, given in Table 7.5, Table 7.4, and

Table 8.2. The average voyage duration for the vehicles in the road-based transport system is found on online mapping sights. For the waterborne transport system, the lead time for passenger and cargo transportation is defined as the maximum duration one can wait for the next vessel departure. The same yields for the road-based transport system when transporting cargo. For the road-based transport system, the lead time for passenger transportation is defined as possible delays and congestion in traffic. When calculating the potential lead time, the duration of cargo and passenger handling is also considered.

9.3.2 Cost of transportation

Cost of transportation is calculated by using the parameters given in Table 9.5, the distances between the various locations, and the installed power and the service speeds of the vessels. Tolls for traveling into and out of Oslo are also included for both private cars and trucks. A fixed cost of 1000 NOK per roundtrip for transporting cargo with trucks is assumed, which will be added to the fuel and toll costs (Oslo Transport AS 2022). The price of diesel is estimated from the average prices in 2022, as the price of electricity. The energy consumption of the vehicles represents the most regular vehicles in Norway of each type.

Table 9.5: Cost coefficients needed for calculating the cost of transportation for both the road-based and the waterborne transport system.

Component	Coefficient	Unit
Diesel price	20	NOK/l
Electricity price	1.7	NOK/kWh
Diesel consumption, ICEV	0.04	l/km
Diesel consumption, truck	0.25	l/km
Electricity consumption, EV	0.18	kWh/km

The time charter rate of the modular vessels is estimated from the equivalent annual cost, which is calculated to be approximately 16.3 MNOK for each vessel. By assuming a ship owner profit of 20%, the time charter rate for a modular vessel is approximately 50 000 NOK per day. It has been assumed that half is covered by the ferry service operators and the other half by cargo owners chartering the vessel.

9.3.3 Weight factors of criteria

Figure 9.4 illustrates the hierarchical structure of the decision problem in the case study. The decision problem is to choose a transport system, either the urban water transport system with modular vessels or the road-based transport system with trucks and private cars.

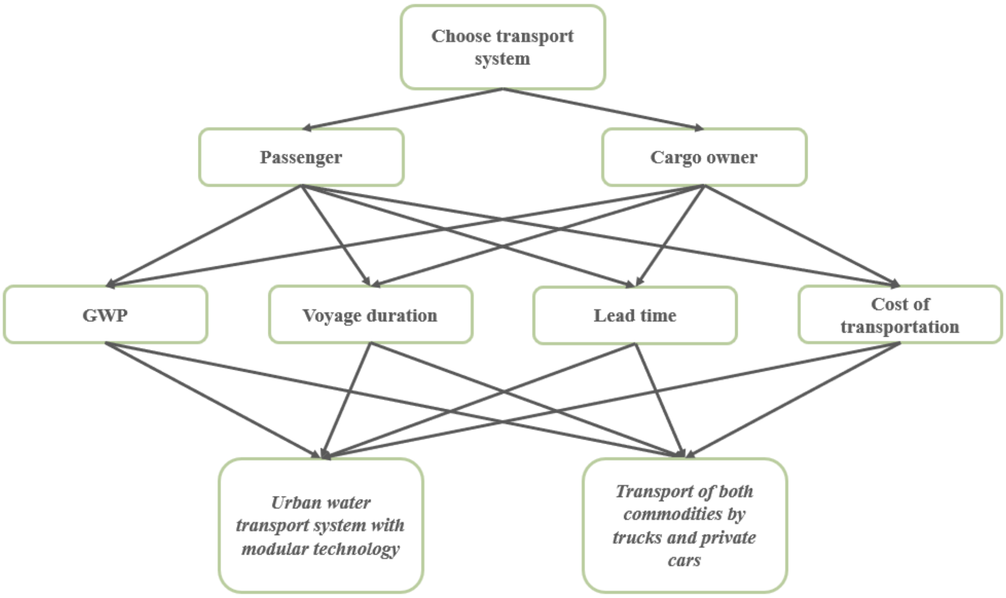


Figure 9.4: The hierarchical structure of the decision problem in the case study.

The preference among the criteria for each decision-maker was established by using the scale of preference presented in Chapter 3. The resulting comparison matrices for each decision-maker can be seen in Equation 9.3 and Equation 9.4.

Decision maker 1, passenger:

$$\begin{bmatrix} & \textbf{GWP} & \textbf{VD} & \textbf{LT} & \textbf{COT} \\ \textbf{GWP} & 1 & 1/5 & 1/3 & 1/6 \\ \textbf{VD} & 5 & 1 & 2 & 1/2 \\ \textbf{LT} & 3 & 1/2 & 1 & 1/4 \\ \textbf{COT} & 6 & 2 & 4 & 1 \end{bmatrix} \tag{9.3}$$

Decision maker 2, cargo owner:

$$\begin{bmatrix} & \textbf{GWP} & \textbf{VD} & \textbf{LT} & \textbf{COT} \\ \textbf{GWP} & 1 & 3 & 2 & 1/2 \\ \textbf{VD} & 1/3 & 1 & 1/4 & 1/5 \\ \textbf{LT} & 1/2 & 4 & 1 & 1/3 \\ \textbf{COT} & 2 & 5 & 3 & 1 \end{bmatrix} \tag{9.4}$$

By using Equation 3.9, the weight factors in Table 9.6 have been established. The most important criterion for commuters is the cost of transportation, with voyage duration as the second highest rated criterion. For cargo owners, cost of transportation also achieved the highest score, followed by GWP impacts.

Table 9.6: The calculated weight factors for each decision-maker, a commuting worker and a and cargo owner, for the four criteria.

Decision maker	**GWP**	**VD**	**LT**	**COT**	**Total**
Commuter	0.062	0.286	0.149	0.503	1.000
Cargo owner	0.268	0.073	0.184	0.475	1.000

Chapter 10

Results from computational studies

This chapter presents the results from the computational studies of the case study for the fjord of Oslo, defined in Chapter 7, based on the optimization models, the life cycle assessments, and the analytical hierarchy process described throughout the report. A discussion of the obtained results will be provided in the next chapter.

First, the results from the fleet scheduling and routing problem are presented, which are used as input in the multi-objective optimization model. The operation profile of the optimal routes in the waterborne transport system is illustrated, showing how the vessels fulfill the daily demand for passengers and cargo by undergoing ship adjustments and configurations. Then the findings from the conducted life cycle assessments will be presented, which is also required input in the MOO model. Lastly, the results from the MOO model will be introduced, presenting the total scores of each transport system.

10.1 Fleet scheduling and routing

Four unique solutions for the multi-commodity vehicle routing problem were found. The solutions are presented in Table 10.1, with the corresponding annual costs, the number of required vessels, and the total daily number of required configurations of the vessels. The daily demand for passengers and cargo can be covered by either 2, 3, or 4 modular vessels, where each vessel undergoes either 2 or 4 configurations from passenger mode to cargo mode and vice versa in each route.

Table 10.1: The unique solutions found for the multi-commodity vehicle routing problem in the fjord of Oslo.

Solution n	Annual cost	Number of vessels	Configurations
1	77.7 MNOK	2	6
2	90.8 MNOK	3	6
3	94.0 MNOK	3	6
4	114.5 MNOK	4	8

A combination of two multiple-routes, out of the 55 generated routes, was the optimal solution for the vehicle routing and scheduling problem. Two vessels will be required for fulfilling the daily passenger and cargo demand in the various locations. The vessels will operate for approximately 16 and 22 hours a day, and the vessels will have to undergo 2 and 4 configurations each during a day, respectively. The annual cost of the urban water transport system will be approximately 77.7 million NOK, which includes investment costs, operational expenditures, sailing costs, port charges, and cargo handling costs. The routes will be referred to as routes number 1 and number 2, respectively. The operational profiles for the two chosen routes are illustrated by Figure 10.1 and Figure 10.2. The capitalized letters refer to what type of commodity is being transported in the single-routes; P for passengers/commuting workers, and C for cargo.

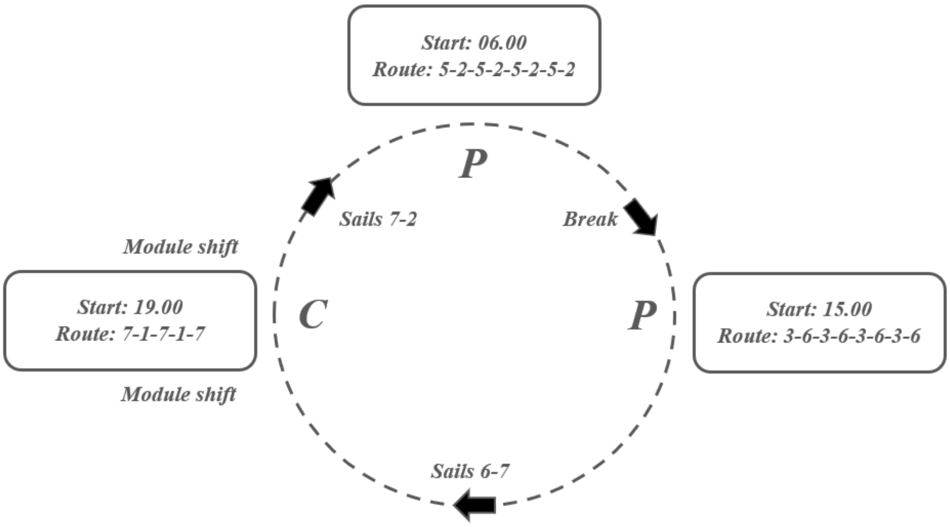


Figure 10.1: The operational profile for route 1 in the waterborne transport system.

The first vessel starts operating at 6 a.m. and covers four passenger crossings between Nesodden and Oslo in the morning. After that, the ship will stay in port until the next commuting period and cover four new passenger crossings. The vessel will then undergo a configuration from passenger mode to cargo mode and transport 40 TEUs of cargo to the city center before it switches back to passenger mode and returns to the starting location. In total, the first vessel will transport 1200 passengers in the morning, 1200 passengers in the late afternoon, and 40 TEUs of cargo in the evening.

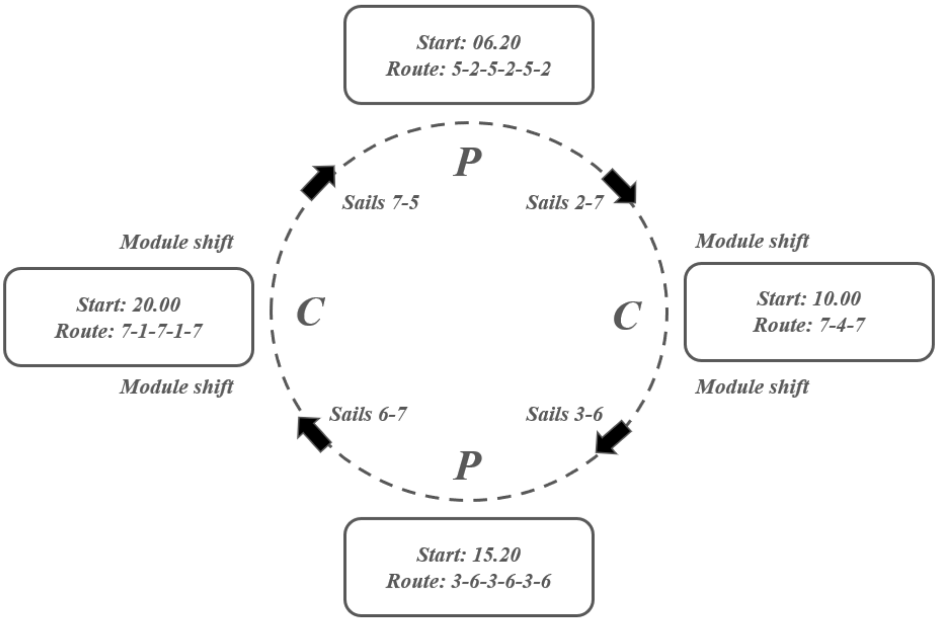


Figure 10.2: The operational profile for route 2 in the waterborne transport system.

The second vessel starts operating at 6.20 a.m. and covers three passenger crossings before it undergoes a module shift in Slemmestad and transports 20 TEUs of cargo to the suburban area Nesodden. When the demand in node 4 is fulfilled, the vessel switches back to passenger mode and covers the three remaining passenger crossings between nodes Oslo and Nesodden. In the evening, the vessel switches back to cargo mode and covers the remaining demand in the city center before it lastly switches back to passenger mode and sails to the route's starting position in node 5. The second vessel will thus transport 900 passengers in the morning, 900 passengers in the late afternoon, and a total of 60 TEUs of cargo between the commuting periods.

The capacity of the vessels is not exceeded in either of the routes, no vessel leaves the same node at the same time, and each vessel returns to its starting location within 24 hours. Thus, the optimal solution comply with the constraints presented in Chapter 5 and Chapter 9.

10.2 Results from life cycle assessments

By using the Ecoinvent 2.2 life cycle inventory database and the impact assessment method ReCiPe with a hierarchist midpoint method in Arda, the global warming potential per passenger and TEU of cargo transported in each transport system has been found. The GWP impacts can be seen in Table 10.2 and Table 10.3, and they are given in kg CO_2-equivalents.

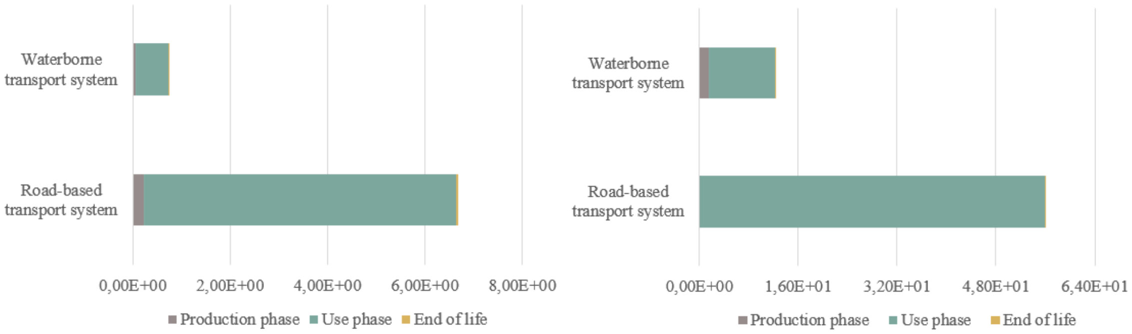
Table 10.2: GWP impacts per passenger and TEU of cargo transported in the road-based transport system, given in kg CO_2 equivalents.

Global warming potential	**Amount**	**Unit**
Per passenger	6.69E+00	kg CO_2-eq
Per TEU	5.59E+01	kg CO_2-eq

Table 10.3: GWP impacts per passenger and TEU of cargo transported by the modular vessels, given in kg CO_2 equivalents.

Global warming potential	**Amount**	**Unit**
Per passenger	7.29E-01	kg CO_2-eq
Per TEU	1.23E+01	kg CO_2-eq

The GWP impacts per passenger and TEU transported are over nine and almost five times larger for the road-based transport system compared to the waterborne transport system, respectively. By looking into the vector of impact potentials by each process, the GWP impacts per passenger and TEU transported for each process included in the LCAs of both systems were found, illustrated in Figure 10.3. The operation phase dominates both systems, with the largest contributor of all being operation of the ICEVs running on diesel.



(a) GWP per PAX transported.

(b) GWP per TEU transported.

Figure 10.3: The global warming potential arising from the different processes included in the LCAs of the two transport systems.

The CO_2 emissions from the end-of-life phase account for only a minor percentage of the total GWP impacts, which agrees with the findings from the investigated LCAs presented in the literature review in Chapter 3. According to these LCAs, the share of the GWP impacts from the production phase should be somewhat larger for both transport systems, which was predicted due to the lack of input data for these processes. Despite this, the results are found to be consistent with the goal and scope of the LCAs defined in Chapter 6.

10.3 Multi-objective decision making

From the multi-objective optimization model, the urban water transport system with modular vessels was found to be the alternative with the highest total score, i.e., the transport system with the best performance with regards to the highest rated criteria. The total score of the waterborne transport system was 0.903 out of 1. In comparison, the score of the road-based transport system was 0.724 out of 1.

Table 10.4 presents the normalized utilities of each criterion for each transport system. The GWP impacts per passenger and TEU transported are both lowest for the waterborne transport system and therefore have a utility of 1. The second highest utility is for the criteria cost of transportation for the waterborne transport system, followed by the cost of transportation for the road-based transport system.

Table 10.4: The utility U of criterion c for transport alternative a.

Utility	**GWP**	**Voyage duration**	**Lead time**	**Cost of transportation**
Urban water transport system	1.000	0.808	0.747	0.959
Road-based transport system	0.164	0.646	0.833	0.905

Table 10.5 presents the averaged weight factors for each criterion. The criteria cost of transportation obtained the highest weight factor as it was rated highest for both decision-makers in the analytical hierarchy process. On the other hand, global warming potential is considered the least essential criterion, even though it was rated second highest by the cargo owner.

Table 10.5: The averaged weight factors w for criterion c.

Criterion	**GWP**	**Voyage duration**	**Lead time**	**Cost of transportation**	**Total**
Weight factors	0.165	0.179	0.167	0.489	1.000

The highest score in each transport system is obtained for the criteria cost of transportation, as seen in Table 10.6. The criteria obtained the highest weight factor from the AHP method for both transport systems, for the commuting worker in the urban water transport system and the cargo owner in the road-based transport system. Even though the GWP impact is considered the least important criterion, it obtained the third highest score of all the criteria for the urban water transport system. This is a consequence of the measured performances of the criterion for the transport systems, as the criteria have a utility of 1 in the urban water transport system and only 0.164 in the road-based transport system.

Table 10.6: The scores of each criterion in the waterborne transport system and the road-based transport system.

Scores	**GWP**	**Voyage duration**	**Lead time**	**Cost of transportation**
Urban water transport system	0.165	0.145	0.124	0.469
Road-based transport system	0.027	0.116	0.139	0.442

Chapter 11

Discussion of results and methodologies

This chapter includes a discussion of the obtained results presented in Chapter 10 and the methodologies and approaches used for finding these results. Throughout this thesis, several assumptions have been made, which will be addressed and discussed with regard to the level of influence on the final results. Sensitivity analyses have been performed to investigate how the multi-objective optimization model performs when variations in the most uncertain input parameters are made. These parameters are related to the maturity of required technology, fluctuations in the market, the representation of the decision makers' preferences, and certain simplifications of cost estimations done throughout this thesis.

A discussion of the value of evaluating and comparing the transport systems to each other by the use of the multi-objective optimization model is provided, aiming to point out the strengths and weaknesses of the optimization model. The area of use of the MOO model is also evaluated with respect to applicability and flexibility. Lastly, the chapter discusses the potential and related challenges of applying autonomous functions to the vessels as proposed in Chapter 8, and gives recommendations for further work and research.

11.1 Assumptions in model development

The results from the developed optimization models and the conducted life cycle assessments heavily depend on the input parameters. Therefore, assumptions that largely influence the results of the computational studies will be addressed and discussed regarding their importance to the obtained results.

11.1.1 Availability of vessel technologies

As discussed in Chapter 8, no modular vessel concept for combined transportation of passengers and cargo exists today. A few pilot projects, such as Medstraum (2021), are under development, but to the author's knowledge, these vessels will not undergo daily configurations for switching between passenger and cargo segments in such a short period of time considered in this thesis. Thus, the scope and development requirements needed for financing and developing such a concept are uncertain. Furthermore, there are significant differences in which criteria passenger vessels and cargo vessels must fulfill to be approved by international and national authorities for being allowed to operate, within the construction of the vessels, facilities on board, and so on.

11.1.2 Uncertainty in cost and duration parameter estimates

Fluctuations in markets make it difficult to predict certain cost coefficients, such as the price of diesel, electricity, building material, etc. Therefore, the cost coefficients used in this thesis are based on the market situation of the last couple of years and do not reflect the actual market price today or in the future.

As previously discussed, the concept of combined transportation of passengers and cargo is relatively unexplored. Thus, a simplified approach (2015) for estimating the investment and operational expenditures of the modular vessels was used. The cost of transportation for the ships in both modes has been estimated from investment costs, the operational expenditures of the transport system, an assumed ship owner profit, and expenses related to sailing, port charges, and cargo handling costs.

Fluctuations in electricity prices make it difficult to estimate the cost of each crossing and thus the ticket price for passengers. According to SSB (2022c) the Norwegian electricity price has increased by over 8% over the last three months. Additionally, the ferry industry often achieves governmental funding as county municipalities are in charge of the local public transport, and the government has committed to facilitating more environmentally friendly public transport (Samferdselsdepartementet 2018).

Market fluctuations also make it challenging to predict diesel and road toll costs. Since 2021 the price of diesel has increased by 40% (SSB 2022d). Additionally, a fixed cost of 1000 NOK has been assumed per roundtrip for transportation of cargo with trucks based on prices set by Oslo Transport AS (2022). The price yields for a truck with a load capacity of 12 tonnes, and the prices might be higher for the trucks investigated in this thesis.

The duration of attaching and detaching the passenger module by using cranes is assumed to be 1 hour. The duration of this process will depend on the technology used for performing this task, in addition to the level of effectiveness, maturity of technology, and requirements and regulations given by the relevant maritime administration, as discussed in the last section.

11.1.3 A consideration of customer preferences

The multi-objective optimization model heavily depends on the weight factors of the criteria defined in Chapter 7. In this thesis, the author performed a pairwise comparison of the criteria for both decision-makers. It might thus not fully represent the actual preferences of the relevant decision-makers.

The criteria cost of transportation was rated as the most important criteria, as seen in Table 9.6, followed by voyage duration, lead time, and lastly global warming potential impacts. If the criterion potential lead time was rated highest, where the utility of the road-based system is higher than for the waterborne system, the optimal solution found from the MOO model might be different. To use the results from the MOO model in a strategic planning process, the weight factors should be based on a greater basis of opinions provided by the relevant decision-makers influential to the decision that shall be made.

11.1.4 Raw data used in the life cycle assessments

When conducting the life cycle assessments of the urban water transport system and the road-based transport system, only the major contributors to global warming potential impacts within each lifecycle phase were accounted for. When such simplifications are performed, it is vital to be consistent in selecting processes to be included to achieve as fair a basis for comparison as possible.

The impacts of producing required propulsion systems were included for neither of the transport systems. The conducted LCAs of electric ferries presented in Chapter 3 found that the construction of propulsion system was the third largest contributor to GWP impacts. The production of required batteries accounted for almost half of the greenhouse gas emissions. The production of batteries and engines was also the third largest contributor to GWP impacts for the electric vehicles, and the production of engines was the fourth major contributor for conventional vehicles.

When assessing the GWP impacts of the road-based transport system, the processes for construction and end-of-life treatment for the private cars were assumed for the trucks in the transport system due to the lack of raw data for conventional trucks. The quantity of materials and energy required for these processes were scaled up to a level the author assumed to be reasonable. Thus, it has been anticipated that the life cycle inventory of the trucks is somewhat deficient. Nevertheless, the LCA performed by Espegren (2021) studied in Chapter 3 showed that the construction phase and the end-of-life phase for the trucks were of minor importance compared to the GWP impacts from the use phase. This yields the results of the conducted LCA, and the deficient inventory has thus been accepted for the scope of this thesis.

11.2 Sensitivity analyses

As discussed in Section 11.1 several assumptions have been made throughout this thesis, some of which substantially affect the results of the computational studies. To investigate the robustness of the found optimal solution, several scenarios have been studied where input parameters and weight factors have been altered compared to the original input, hereby referred to as the base case.

11.2.1 Alterations in input parameters

Test instances for alterations in the discussed input parameters used for finding the performances and utilities of the different criteria for each transport system have been studied. The following instances have been explored:

Instance 1: A governmental funding of 30% for the ticket prices for passengers.

Instance 2: The fixed cost of transporting cargo with trucks is increased by 50%.

Instance 3: The price of electricity is increased by 10%.

Instance 4: The diesel price is decreased by 20%.

Instance 5: Configurations of the modular vessels will have a duration of 2 hours.

Instance 6: The car occupancy is increased to 2 passengers per car.

Table 11.1: A representation of the sensitivity of the obtained solution when doing alternations to input parameters. The difference refers to the increases/decreases in the total scores of the systems compared to the original solution.

Test instance	**Alterations**	**Scores**	**Difference**
1	Governmental funding	(**0.903**, 0.665)	+0%, -8%
2	Increased fixed cost, trucks	(**0.923**, 0.678)	+2%, -6%
3	Increase in el-price	(**0.898**, 0.731)	-1%, +1%
4	Decrease in diesel price	(**0.893**, 0.743)	-1%, +3%
5	Increased conf. duration	(**0.867**, 0.776)	-4%, +7%
6	Increased PAX occupancy	(**0.886**, 0.774)	-2%, +7%

The results from the sensitivity analysis, presented in Table 11.1, show that the urban water transport system obtains the highest score for all test scenarios, even though four out of six scenarios benefit the road-based transport system. An interesting observation can be made for test instance 5; The increased configuration duration for the modular vessels leads to a need for an extra ship in the waterborne transport system. An additional vessel leads to increased GWP impacts and increased cost of transportation for both commuters and cargo owners. Despite this, the waterborne transport system obtains a higher score than the road-based transport system.

The results from the sensitivity analysis of the obtained solution when addressing the uncertainty in several input parameters provides a further basis for investigating the influence of the weight factors.

11.2.2 Alterations in weight factors

To illustrate the importance of the weight factors for the obtained results, a sensitivity analysis has been conducted where alterations in the weight factors have been done. As the weight factors are uncertain and determined by the relevant decision-makers, the sensitivity analysis has studied the extremes. The extremes refer to the weight factors that are most beneficial for each decision-maker and which influence the obtained results the most.

By a ”trial and error” method, the extremes of the weight factors were found for the base case. The base case, and the defined instances listed in the previous section, were thus tested for the following scenarios:

Scenario 1: In benefit for road-based transport system

$$w_c = (0.025, 0.075, 0.675, 0.225)$$

Scenario 2: In benefit for waterborne transport system

$$w_c = (0.750, 0.083, 0.083, 0.083)$$

Table 11.2: A representation of the sensitivity of the obtained solution when using the extremes of the weight factors. The difference refers to the increases/decreases in the total scores of the systems compared to the original solution.

Test instance	Weight factor scenario	Scores	Difference
Base case	1	(0.806, **0.819**)	-11%, +13%
	2	(**0.959**, 0.322)	+6%, -56%
1	1	(**0.806**, 0.791)	-11%, +9%
	2	(**0.959**, 0.312)	+6%, -57%
2	1	(**0.815**, 0.797)	-10%, +10%
	2	(**0.962**, 0.314)	+7%, -57%
3	1	(0.803, **0.822**)	-11%, +14%
	2	(**0.958**, 0.322)	+6%, -56%
4	1	(0.801, **0.827**)	-11%, +14%
	2	(**0.958**, 0.325)	+6%, -55%
5	1	(0.789, **0.841**)	-13%, +16%
	2	(**0.953**, 0.355)	+6%, -51%
6	1	(0.797, **0.840**)	-12% +16%
	2	(**0.956**, 0.343)	+6%, -53%

The results from the sensitivity analysis, presented in Table 11.2, show that for most of the test instances, the optimal solution alternates between the road-based and the waterborne transport system, depending on the underlying weight factors. However, exceptions can be found for test instances 1 and 2, where governmental funding of ticket prices is assumed, and the fixed cost of cargo transportation with trucks is increased. The waterborne transport system obtains the highest score for both weight factor scenarios in these test instances.

Another interesting observation is that the score of the waterborne transport system has the potential to increase by 7% at the expense of an almost 60% decrease in the score of the road-based transport system. However, for the opposite case, the score of the road-based transport system increases by 16%, but only at the expense of a 13% decrease in the score of the waterborne system. This observation shows that the score of the waterborne transport system is less dependent on the weight factors provided by the decision-makers, as it obtains more consistent results across all test instances and alternations in weight factors than the score of the road-based transport system.

11.3 Comparison of multi-objective optimization models

In Chapter 4, two multi-objective optimization models were proposed. Computational studies have also been performed for the alternative multi-objective optimization model. The waterborne transport system obtained the highest score for this model formulation as well, with a total score of 0.920. The road-based transport system achieved a total score of 0.694. Table 11.3 presents the scores of each criterion for each transport system.

For the waterborne transport system, the scores of the criteria voyage duration and cost of transportation have increased compared to the original scores given in Table 10.6. The increase can be explained by the higher level of preference these criteria have for the commuting workers compared to the averaged weight factors, combined with high utilities of the criteria in the waterborne transport system. In comparison, the scores of these criteria in the road-based transport system have decreased due to lower level of preference compared to the averaged weight factors used in the original model formulation.

Table 11.3: The scores of each criterion in the waterborne transport system and the road-based transport system by using the alternative model formulation.

Scores	**GWP**	**Voyage duration**	**Lead time**	**Cost of transportation**
Urban water transport system	0.165	0.165	0.120	0.470
Road-based trasnport system	0.033	0.078	0.142	0.441

The solution from the alternative model has also been tested for alterations in input parameters and weight factors to see how sensitive the obtained solution is. When doing modifications in the input parameters, the increases and decreases in the obtained solution are similar to the cases of the original solution analyzed in the former section. Thus, the robustness of the solution from the alternative optimization model is similar to the original model for alterations in input parameters. Despite this, the original formulation gives more consistent results when doing alterations in weight factors, whereas the alternative formulation results in a higher deviation in the obtained solution. Therefore, the original MOO model is less sensitive to extremes and is thus considered to be more robust and consistent.

11.4 Value of the optimization model

The focus of the discussion has been on the results obtained from the conducted computational studies and the uncertainty of the input parameters used in this thesis. This section discusses the value of the developed optimization decision-making model and elaborates on the strengths and weaknesses of the model.

The presented multi-objective optimization model is an extension of the weighted-sum model presented in Equation 3.4-3.7 in Chapter 3, and is rather simple in it's form. The model simply calculates an average score of an alternative based on criteria and preferences established by the decision-makers, based on the performances of each transport system. The model's simplicity makes it more applicable to other decision-making problems, as the model is not adapted to the decision-making problem defined in this thesis. Additionally, the model can consider multiple decision-makers, which gives it a wider range for handling complex decision-making problems, which is often the case in strategic planning processes. When it comes to construction and development projects in the transport industry, large investments and considerable planning and execution processes are often required. Thus it is most important to consider the opinions of all relevant decision-makers to obtain satisfactory long-term results.

A weakness related to the simplicity of the MOO model might be that it does not capture the full complexity of decision-making problems. As previously mentioned, the model calculates an averaged score of an alternative based on averaged weight factors and normalized utilities and performances. Such an approach raises questions about the extent to which the results can be called optimal, as they most likely will be obtained at the expense of some decision-makers' preferences. Thus, it could be valuable to extend the model to fulfill a minimum satisfaction for each decision-maker. A proposed extension of the decision-making model is to add a constraint ensuring that the difference in the utilities of a criterion for different decision-makers can not be less than a certain value, forcing the alternatives to undergo modifications and improvements if the discrepancies are too significant. Another proposed extension is to add constraints ensuring that the averaged weight factors do not go below a specific limit for each decision-maker.

The proposed decision-making model does not capture future uncertainty, such as fluctuations in markets, possible future regulations, etc. The results from the sensitivity analysis presented in Table 11.1 show that the waterborne transport system obtained the highest score for both changes in prices of electricity and diesel. But, combined with alternations in weight factors, the outcome might be different. Thus, it could be valuable to extend the model to consider various future scenarios to better handle future uncertainty. The extension could simply be done by adding a set P, which consists of different periods, and by extending the decision variable to the following:

$$x_{ap} = \begin{cases} 1 & \text{if alternative } a \text{ is chosen in period } p \\ 0 & \text{otherwise} \end{cases}$$

This extension will require more extensive preliminary work as weight factors for each criterion by each decision-maker will have to be computed for each defined future scenario. Additionally, future scenarios may result in decision-makers considering other criteria more important than today. Thus, this extension may also require decision-makers to define relevant criteria and perform pairwise comparisons of all criteria for each defined period.

11.5 Potential for autonomous operation

The concept of autonomy was discussed in Chapter 8, and autonomous operation of the modular vessels when transporting cargo was proposed for reducing expenditures related to voyage and operation and for increasing safety at sea. This section discusses the concept concerning its applicability, potential benefits, and related challenges. Even though crew costs are not accounted for in either of the optimization models, it is included in the discussion to highlight potential benefits.

One of the key drivers for exploring the possibility of autonomous operation of vessels is to reduce voyage expenditures in terms of crew costs. In Chapter 8, the annual crew costs were found to be reduced by approximately 7.8 MNOK per vessel per year if the ships were remotely controlled with seafarers on board only when operating in "passenger mode." Assuming one person is needed for monitoring the vessels from a remote shore control center, with the same salary as a captain and a working shift of 8 hours, the urban water transport system could potentially reduce its annual crew costs by over 13 MNOK.

Regarding the design considerations of the modular vessels, a fully-electric propulsion system facilitates autonomous operation. The modular vessels are expected to sail at a speed of 10 knots when transporting cargo, resulting in a crossing time of approximately 1 hour. For the ships to sail faster and save crew costs, more installed power on board the vessels will be required. The increase in installed power will lead to higher energy consumption and thus result in higher operational costs. Fully or partly unmanned vessels have the possibility of reducing speed to save sailing costs without it influencing the manning costs. Additionally, battery-electric vessels do not require the same maintenance and monitoring as machinery in conventional vessels do. Thus, machinists may not be needed on board the vessels during operation.

However, there are several challenges related to autonomous operation of vessels. The framework of autonomous ships is still under development. IMO is currently developing a regulatory framework for maritime autonomous surface ships and has recently completed a regulatory scoping exercise to analyze relevant ship safety treaties to assess how autonomous vessels could be regulated in the future. Several high-priority issues were found and will have to be addressed at a policy level to determine future work (IMO 2021). Relevant risk-acceptance criteria must be developed and assessed against the risks related to autonomous operation of the system under investigation to realize an autonomous waterborne transportation system.

Ports in large cities often experience heavy traffic due to cargo importation and recreational craft. Even though the modular vessels will sail daily fixed routes, the scope of risk can be unpredictable and thus limit the possibility of implementing autonomous vessels in a specific area. By collecting automatic identification system (AIS) data from the locations under investigation, the traffic density could be found and used to assess the scope of risk for applying autonomous operation during daytime and night.

11.6 Recommendations for further research

Based on the discussion presented in this chapter, the following areas for further research, and extensions and improvements of optimization models and approaches, have been recommended:

- Perform an analytical hierarchy process based on the opinions and preferences of the relevant decision-makers for the transport systems. A survey should be performed to find which criteria the decision-makers find most important and valuable and to map how the decision-makers will rate the different criteria through pairwise comparisons.

- Extend the multi-objective optimization model to include future time periods for facilitating long-term planning and for handling future uncertainty. When deciding on future projects requiring large investments it is important to consider uncertainty and fluctuations in the market.
- To ensure that the decision makers' preferences are considered the model could be extended by adding constraints ensuring that the averaged weight factors are above a certain limit.
- To fully represent and evaluate the environmental impacts of the transport systems, more consistent and detailed life cycle assessments should be performed for both transport systems. The LCAs should aim to include all emissions over the transport systems' whole lifecycles, including the whole value chain from production to end-of-life treatment.
- To further evaluate autonomous operation of the modular vessels the traffic density of the area under investigation should be assessed. This could be done through the use of AIS data, and the risk of autonomous operation should be evaluated to relevant risk-acceptance criteria developed by the IMO and other relevant maritime administrations.

Chapter 12

Conclusions and recommendations

Due to increased urbanization, nearly all big cities suffer from congestion, which has resulted in higher demand and a greater need for efficient and reliable urban transport systems for the movements of cargo and passengers. Road transportation is the main mode of domestic transportation and accounts for nearly 75% of the total greenhouse gas emissions in the EU. The European Commission has set ambitions for Europe to become climate neutral by 2050 and has suggested measures of a modal shift from road transportation to less polluting modes of transportation, such as waterborne transport, to reach their goals. Many of the largest cities in the world are located by water, contributing to the great potential of moving domestic transportation off the road and onto the sea.

It is great potential for combining transportation of passengers with distribution of cargo by waterborne transportation. Passenger ferries connecting urban and sub-urban areas often experience non-service gaps between peak commuting periods. They could thus be used for cargo transportation during these periods to relieve the road network. Combined waterborne transportation could be enabled through modularization technology, where vessels could be configured to alternately transport passengers and cargo by using standardized modules. Throughout this thesis, an urban water transport system consisting of modular vessels as an alternative to road-based transportation has been investigated concerning both economic, social, and environmental impacts.

Some of the major contributions of the conducted work are listed below:

- Formulation of a binary multi-commodity vehicle routing model that aims to find the optimal fleet size and routing for modular vessels alternately transporting cargo and passengers, while minimizing annual costs.

- Formulation of a multi-objective optimization (MOO) model aiming to provide decision support to relevant decision-makers in the transport industry, based on a set of defined criteria and weight factors provided by the decision-makers.
- Case study conducted for the fjord of Oslo, where the optimal fleet size and routing have been found through the use of the multi-commodity vehicle routing model, and where the optimal choice of transportation system has been found for commuters and cargo owners through the use of the MOO model.
- A cradle-to-grave life cycle assessment (LCA) to assess the global warming potential (GWP) impacts of a road-based transport system consisting of ICEVs, EVs, and conventional trucks, and a water-based transport system consisting of battery-electric modular vessels.

A multi-objective optimization model has been developed to provide decision support to two decision-makers, a commuting worker and a cargo owner, when deciding on a mode of transport with regards to a set of criteria they find important. A case study for the fjord of Oslo has been conducted, where a daily supply and demand for passenger and cargo have been defined in the suburban areas Slemmestad and Nesodden, and in the main center of Oslo. The MOO model has been used to evaluate the performances within the criteria ”global warming potential impacts”, ”voyage duration”, ”potential lead time” and ”cost of transportation” for two transport systems; an urban water transport system consisting of battery-electric modular vessels and a road-based transport system consisting of conventional cars, electric cars, and conventional trucks.

Main dimensions, load capacities, and service speeds have been defined for the modular vessels in the waterborne transport system. Through the use of modularization technology, a passenger module will be lifted and installed on the main deck of the vessels when transporting commuting workers. When the vessels are required to transport cargo, the module will be detached and cargo loaded in twenty-foot equivalent units (TEU) will be placed directly on the main deck. The vessels will have a load capacity of 300 passengers and 20 TEUs.

A multi-commodity vehicle routing model has been developed for finding the optimal fleet size and routing for the waterborne transport system consisting of modular vessels. A fleet of two modular vessels is able to fulfill the daily demand for passengers and cargo in the locations Nesodden, Slemmestad, and Oslo. The vessels will undergo 2 and 4 configurations each during a day, from cargo mode to passenger mode and vice versa, and will transport 2100 passengers and 100 TEUs of cargo each day. The annual cost of the waterborne transport system is found to be approximately 77.7 MNOK, including investment costs, operational expenditures, and voyage costs.

Life cycle assessment has been used for finding the global warming potential impacts of each transport system. Only the major contributors to environmental impacts within each lifecycle phase, i.e. the production, operation, and end-of-life treatment phases, were included in the assessments. The GWP impacts per passenger and TEU transported are over nine and almost five times larger for the road-based transport system, respectively, mainly due to the combustion of diesel for the ICEVs and the conventional trucks.

For defining weight factors for each criterion, the analytical hierarchy process has been used. For the passengers, or the commuting workers, the criteria cost of transportation was rated highest, followed by voyage duration, potential lead time, and GWP impacts, respectively. Cost of transportation also obtained the highest score for the cargo owner, followed by GWP, lead time, and voyage duration, respectively.

The results from the multi-commodity vehicle routing model, the LCAs, and the AHPs were then used as input in the multi-objective optimization model. Based on the performances of each transport system in each criterion, and the weight factors set by the decision-makers, the urban water transport system obtained a total score of 0.903, and the road-based system a score of 0.724. Thus, the optimal solution based on the preferences of both decision-makers is found to be the waterborne transport system. This is mainly due to the large difference in utilities for the GWP impacts of each transport system, where the waterborne transport system has obtained the maximal highest score, and due to the performance of the waterborne transport system being approximate 25% higher for the criterion voyage duration.

The robustness of the obtained solutions for the case studies for the fjord of Oslo indicates that the defined urban water transport system consisting of modular vessels can be competitive with a road-based transport system. Even by adding another vessel, leading to increased GWP impacts and increased cost of transportation for both commuters and cargo owners, the waterborne transport system will still be competitive with the road-based transport system. The results from the computational studies thus provide a basis for further research and exploration of the concept.

Bibliography

UNECE (2022). *Transport Statistics Infocard.* URL: https://stats.unece.org/infocard/en/040/ (visited on 10/02/2022).

Pastori, E. et al. (2018). *Research for TRAN Committee - Modal shift in European transport: a way forward.* URL: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/629182/IPOL_STU(2018)629182_EN.pdf (visited on 27/02/2022).

EC (2011). *WHITE PAPER - Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system.* URL: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:en:PDF (visited on 27/02/2022).

Pinchasik, D. R., I. B. Hovi and C. S. Mjøsund (2020). *Crossing Borders and Expanding Modal Shift Measures: Effects on Mode Choice and Emissions from Freight Transport in the Nordics.* URL: https://www.platonklima.no/wp-content/uploads/2021/04/Daniel-Ruben-Crossing-borders.pdf (visited on 20/03/2022).

EC (2022a). *Multimodal and combined transport.* URL: https://transport.ec.europa.eu/transport-themes/logistics-and-multimodal-transport/multimodal-and-combined-transport_en (visited on 20/03/2022).

ECMC (2001). *Short Sea Shipping in Europe.* URL: https://www.oslohavn.no/no/meny/tjenester/priser-og-forretningsvilkar/ (visited on 10/02/2022).

SSB (2020). *Mer gods fraktet med tog og båt.* URL: https://www.ssb.no/transport-og-reiseliv/artikler-og-publikasjoner/mer-gods-fraktet-med-tog-og-bat (visited on 15/02/2022).

Statista (2021). *Ranking of the longest coastlines in the world.* URL: https://www.statista.com/statistics/506526/longest-coastlines-in-the-world/ (visited on 02/02/2022).

EC (2020). *Majority commuted less than 30 minutes in 2019.* URL: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20201021-2 (visited on 20/03/2022).

SSB (2022a). *Domestic transportation.* URL: https://www.ssb.no/en/statbank/table/03982/ (visited on 20/03/2022).

Kommuneprofilen (2022). *Innpendling til valgt arbeidskommune - etter bostedskommune. 2000-2017.* URL: https://www.kommuneprofilen.no/profil/sysselsetting/DinRegion/syss_pend_strom_region.aspx (visited on 20/03/2022).

EC (2022b). *Transport and the Green Deal.* URL: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en (visited on 08/02/2022).

SSB (2021). *Utslipp til luft.* URL: https://www.ssb.no/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft (visited on 10/02/2022).

Andersen, J. and T. Hammervoll (2021). *Varelevering kveld og natt.* URL: https://www.tiltak.no/b-endre-transportmiddelfordeling/b-6-gods-og-varetransport-i-by/b-6-2/ (visited on 15/02/2022).

WTP (2021). *Strategic Research and Innovation Agenda for the Partnership on Zero-Emission Waterborne Transport.* URL: https://www.waterborne.eu/images/210601_SRIA_Zero_Emission_Waterborne_Transport_1.2_final_web_low.pdf (visited on 26/02/2022).

IMO (2020). *Fourth Greenhouse Gas Study 2020.* URL: https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx (visited on 02/03/2022).

EEA (2022). *Rail and waterborne best for low-carbon motorised transport.* URL: https://www.eea.europa.eu/publications/rail-and-waterborne-transport (visited on 04/03/2022).

SSB (2018). *Godstransport på kysten.* URL: https://www.ssb.no/statbank/table/03648/tableViewLayout1/ (visited on 15/03/2022).

Tanko, M., H. Cheemakurthy and K. Garme (Feb. 2018). 'Urban waterborne public transport systems: An overview of existing operations in world cities'. In: pp. 3–77.

Shaqiri, A. B. (2014). 'Management Information System and Decision-Making'. In: *Academic journal of interdisciplinary studies MCSER publishing, Rome-Italy* 3.

Choi, M., S. O. Erikstad and H. Chung (2018). 'Operation platform design for modular adaptable ships: Towards the configure-to-order strategy'. In: *Ocean Engineering* 163, pp. 85–93.

Erikstad, S. O. (2009). 'Modularisation in shipbuilding and modular production'. In: *Innovation in Global Maritime Production.*

TrAM (2021). *This is what modularization looks like!* URL: https://tramproject.eu/2021/09/29/this-is-what-modularization-looks-like/ (visited on 07/02/2022).

Ulstein (2019). *Cost-effective vessel conversion using standardised modules.* URL: https://ulstein.com/news/cost-effective-vessel-conversion-using-standardised-modules (visited on 07/02/2022).

Ulrich, K. T. and S. D. Eppinger (2016). *Product Design and Development.* McGraw-Hill Education.

EC (2003). *Inland Waterway Transport.* URL: https://project-iwts20.eu/wp-content/uploads/2020/01/brochure_ilandwaterways_en.pdf (visited on 20/02/2022).

Scala, N. M. et al. (2012). *Multi-objective Decision Analysis for Workforce Planning: A Case Study.* URL: http://d-scholarship.pitt.edu/22686/1/Scala_et_al_2012.pdf (visited on 10/04/2022).

Caramia, M. and P. Dell'Olmo (2008). *Multi-objective Management in Freight Logistics.* Springer.

Guerra, A. and M. M. Jenssen (2014). *Multi Criteria Decision Analysis (MCDA) in the Norwegian Maritime Sector.* URL: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/242536/752188_FULLTEXT01.pdf?sequence=1&isAllowed=y (visited on 10/04/2022).

Wang, I. (2018). 'Multicommodity Network Flows: A Survey, Part I: Applications and Formulations'. In: *International Journal of Operations Research* 15, pp. 145–153.

Fagerholt, K. (1999). 'Optimal fleet design in a ship routing problem'. In: *International Transactions in Operational Research* 6.5, pp. 453–464. URL: https://www.sciencedirect.com/science/article/pii/S0969601699000106.

Galaaen, J. S. (2020). *Comparative Life Cycle Assessment of a Diesel Electric and a Battery Electric Ferry.* URL: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2755475?show=full (visited on 08/03/2022).

Kullmann, A. B. (2016). *A Comparative Life Cycle Assessment of Conventional and All-Electric Car Ferries.* URL: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2491124/15570_FULLTEXT.pdf?sequence=1&isAllowed=y (visited on 08/03/2022).

Ellingsen, L. A. W., B. Singh and A. H. Strømman (2016). 'The size and range effect: lifecycle greenhouse gas emissions of electric vehicles'. In: *Environmental Research Letters* 11.5. URL: https://doi.org/10.1088/1748-9326/11/5/054010.

Espegren, K. Aa., G. K. Booto and R. Hancke (2021). 'Comparative life cycle assessment of heavy-duty drivetrains: A Norwegian study case'. In: *Transportation Research Part D: Transport and Environment* 95.0. URL: https://www.sciencedirect.com/science/article/pii/S1361920921001395.

Golsteijn, L. (2022). *Life Cycle Assessment (LCA) explained.* URL: https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/#h-what-is-a-life-cycle-assessment-lca (visited on 16/03/2022).

Hauschild, M. Z. and M. A. J. Huijbregts (2015). *Life Cycle Impact Assessment.* Springer, pp. 1–16.

Oslo Kommune (2022). *Næringsliv og sysselsetting.* URL: https://www.oslo.kommune.no/statistikk/boliger-byggevirksomhet-arbeids-og-naringsliv/naringsliv-sysselsetting-og-pendling/#gref (visited on 15/03/2022).

Ormevik, A. B. (2020). *Using Optimization to Evaluate the Potential for Multimodal Cago Distribution in a Regional Port.* URL: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2780106 (visited on 10/04/2022).

Corvus Energy (2022). *Why Energy Storage.* URL: https://corvusenergy.com/sustainability/why-battery/ (visited on 15/05/2022).

Wärtsilä (2022). *Charging Marine Vessels.* URL: https://www.wartsila.com/marine/build/electrical-and-power-systems/shore-power/charging (visited on 16/05/2022).

NFAS (2018). *Why autonomous.* URL: https://nfas.autonomous-ship.org/why-autonomous/ (visited on 16/04/2022).

EMSA (2020). *Annual Overview of Marine Casualties and Accidents 2020.* URL: http://emsa.europa.eu/csn-menu/items.html?cid=14&id=4266 (visited on 16/04/2022).

IMO (2021). *Autonomous shipping.* URL: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx (visited on 17/05/2022).

NMA (2019). *Bemanningsfastsettelse Ferjer.* URL: https://www.sdir.no/contentassets/559d1fc60b244a98be083fa36f21c838/bemanningsfastsettelse-ferje.pdf (visited on 28/05/2022).

SSB (2022b). *Lønn.* URL: https://www.ssb.no/statbank/table/11420 (visited on 28/05/2022).

Amdahl, J., A. Endal and G. Fuglerud (2015). *TMR4105 - Marin Teknikk Grunnlag.* Akademika.

Oslo Havn KF (2022). *Priser og forretningsvilkår 2022.* URL: https://www.oslohavn.no/no/meny/tjenester/priser-og-forretningsvilkar/ (visited on 12/05/2022).

Ringström, A. (2019). 'Life Cycle Assessment of a Road Ferry'. In: URL: https://www.diva-portal.org/smash/get/diva2:1327163/FULLTEXT01.pdf.

Oslo Transport AS (2022). *Prisliste.* URL: https://www.oslo-transport.no/prisliste/ (visited on 09/05/2022).

SSB (2022c). *Elektrisitetspriser.* URL: https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitetspriser (visited on 27/05/2022).

Samferdselsdepartementet (2018). *Handlingsplan for kollektivtransport.* URL: https://www.regjeringen.no/contentassets/75a2e25ed8af4eb5ae32b63c1b3d8353/handlingsplan-for-kollektivtransport.pdf (visited on 27/05/2022).

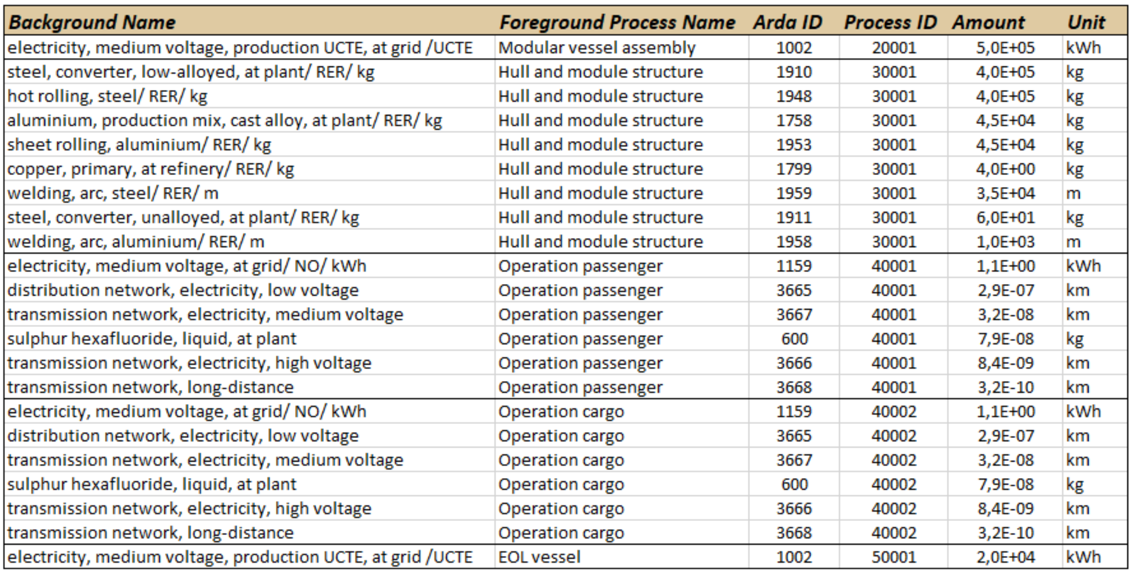
SSB (2022d). *Sales of petroleum products and liquid biofuels.* URL: https://www.ssb.no/statbank/table/09654/tableViewLayout1/ (visited on 27/05/2022).

Appendices

Appendix A

Life Cycle Inventory of Modular Vessels

A.1 Background Processes



Background Name	***Foreground Process Name***	***Arda ID***	***Process ID***	***Amount***	***Unit***
electricity, medium voltage, production UCTE, at grid /UCTE	Modular vessel assembly	1002	20001	5,0E+05	kWh
steel, converter, low-alloyed, at plant/ RER/ kg	Hull and module structure	1910	30001	4,0E+05	kg
hot rolling, steel/ RER/ kg	Hull and module structure	1948	30001	4,0E+05	kg
aluminium, production mix, cast alloy, at plant/ RER/ kg	Hull and module structure	1758	30001	4,5E+04	kg
sheet rolling, aluminium/ RER/ kg	Hull and module structure	1953	30001	4,5E+04	kg
copper, primary, at refinery/ RER/ kg	Hull and module structure	1799	30001	4,0E+00	kg
welding, arc, steel/ RER/ m	Hull and module structure	1959	30001	3,5E+04	m
steel, converter, unalloyed, at plant/ RER/ kg	Hull and module structure	1911	30001	6,0E+01	kg
welding, arc, aluminium/ RER/ m	Hull and module structure	1958	30001	1,0E+03	m
electricity, medium voltage, at grid/ NO/ kWh	Operation passenger	1159	40001	1,1E+00	kWh
distribution network, electricity, low voltage	Operation passenger	3665	40001	2,9E-07	km
transmission network, electricity, medium voltage	Operation passenger	3667	40001	3,2E-08	km
sulphur hexafluoride, liquid, at plant	Operation passenger	600	40001	7,9E-08	kg
transmission network, electricity, high voltage	Operation passenger	3666	40001	8,4E-09	km
transmission network, long-distance	Operation passenger	3668	40001	3,2E-10	km
electricity, medium voltage, at grid/ NO/ kWh	Operation cargo	1159	40002	1,1E+00	kWh
distribution network, electricity, low voltage	Operation cargo	3665	40002	2,9E-07	km
transmission network, electricity, medium voltage	Operation cargo	3667	40002	3,2E-08	km
sulphur hexafluoride, liquid, at plant	Operation cargo	600	40002	7,9E-08	kg
transmission network, electricity, high voltage	Operation cargo	3666	40002	8,4E-09	km
transmission network, long-distance	Operation cargo	3668	40002	3,2E-10	km
electricity, medium voltage, production UCTE, at grid /UCTE	EOL vessel	1002	50001	2,0E+04	kWh

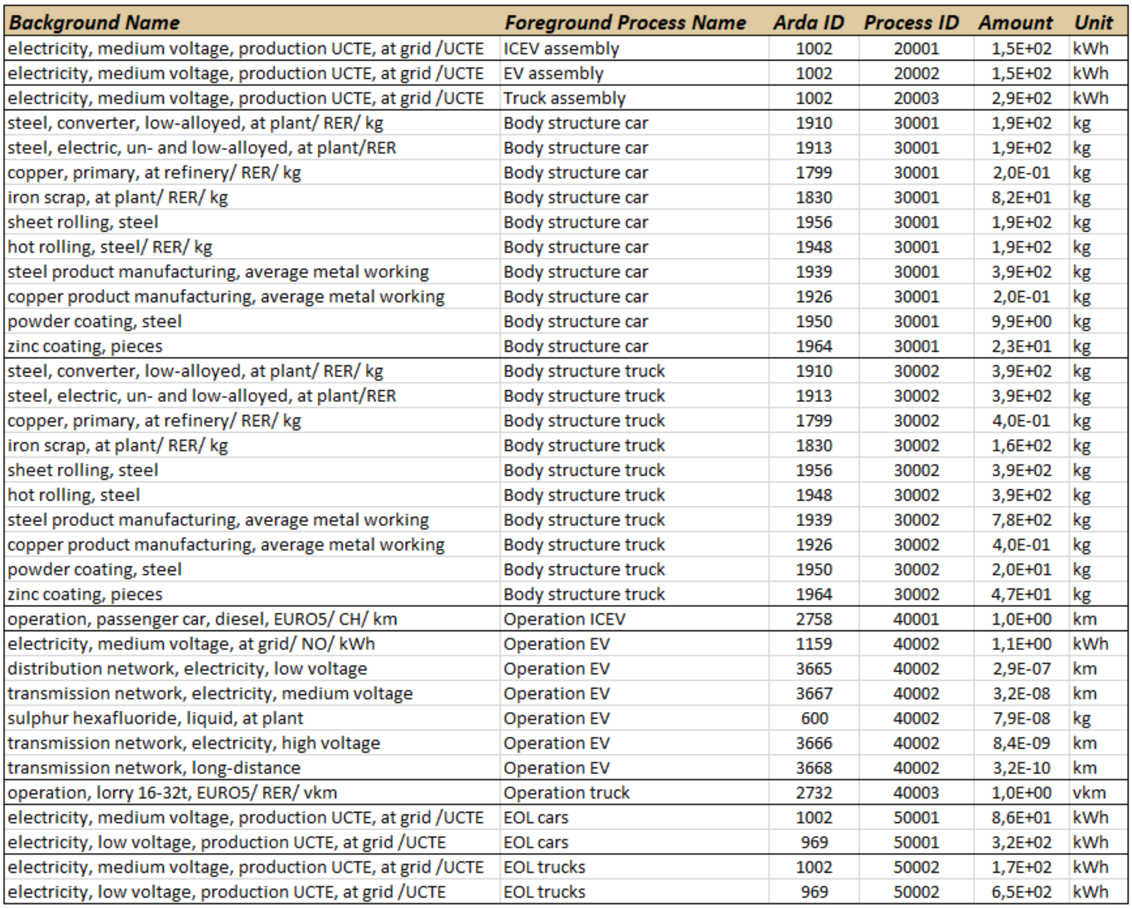
A.2 Foreground Processes

				A $_{ff}$					
Full Name	***Process ID***	y_f	***Unit***	***Modular water transport system***	***Modular vessel assembly***	***Hull and module structure***	***Operation passenger***	***Operation cargo***	***EOL vessel***
Modular water transport system	Modular water transport system	1	p						
Modular vessel assembly	Modular vessel assembly		p	2					
Hull and module structure	Hull and module structure		p		1				
Operation passenger	Operation passenger		kWh	2,82E+08					
Operation cargo	Operation cargo		kWh	2,20E+08					
EOL vessel	EOL vessel		p	2					

Appendix B

Life Cycle Inventory of ICEVs, EVs, and Trucks

B.1 Background Processes



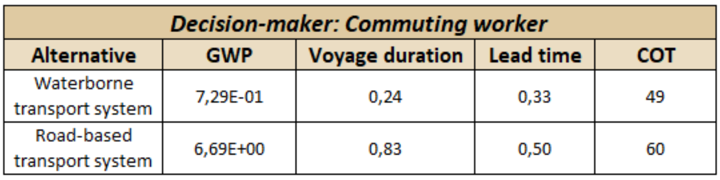
Background Name	Foreground Process Name	Arda ID	Process ID	Amount	Unit
electricity, medium voltage, production UCTE, at grid /UCTE	ICEV assembly	1002	20001	1,5E+02	kWh
electricity, medium voltage, production UCTE, at grid /UCTE	EV assembly	1002	20002	1,5E+02	kWh
electricity, medium voltage, production UCTE, at grid /UCTE	Truck assembly	1002	20003	2,9E+02	kWh
steel, converter, low-alloyed, at plant/ RER/ kg	Body structure car	1910	30001	1,9E+02	kg
steel, electric, un- and low-alloyed, at plant/RER	Body structure car	1913	30001	1,9E+02	kg
copper, primary, at refinery/ RER/ kg	Body structure car	1799	30001	2,0E-01	kg
iron scrap, at plant/ RER/ kg	Body structure car	1830	30001	8,2E+01	kg
sheet rolling, steel	Body structure car	1956	30001	1,9E+02	kg
hot rolling, steel/ RER/ kg	Body structure car	1948	30001	1,9E+02	kg
steel product manufacturing, average metal working	Body structure car	1939	30001	3,9E+02	kg
copper product manufacturing, average metal working	Body structure car	1926	30001	2,0E-01	kg
powder coating, steel	Body structure car	1950	30001	9,9E+00	kg
zinc coating, pieces	Body structure car	1964	30001	2,3E+01	kg
steel, converter, low-alloyed, at plant/ RER/ kg	Body structure truck	1910	30002	3,9E+02	kg
steel, electric, un- and low-alloyed, at plant/RER	Body structure truck	1913	30002	3,9E+02	kg
copper, primary, at refinery/ RER/ kg	Body structure truck	1799	30002	4,0E-01	kg
iron scrap, at plant/ RER/ kg	Body structure truck	1830	30002	1,6E+02	kg
sheet rolling, steel	Body structure truck	1956	30002	3,9E+02	kg
hot rolling, steel	Body structure truck	1948	30002	3,9E+02	kg
steel product manufacturing, average metal working	Body structure truck	1939	30002	7,8E+02	kg
copper product manufacturing, average metal working	Body structure truck	1926	30002	4,0E-01	kg
powder coating, steel	Body structure truck	1950	30002	2,0E+01	kg
zinc coating, pieces	Body structure truck	1964	30002	4,7E+01	kg
operation, passenger car, diesel, EURO5/ CH/ km	Operation ICEV	2758	40001	1,0E+00	km
electricity, medium voltage, at grid/ NO/ kWh	Operation EV	1159	40002	1,1E+00	kWh
distribution network, electricity, low voltage	Operation EV	3665	40002	2,9E-07	km
transmission network, electricity, medium voltage	Operation EV	3667	40002	3,2E-08	km
sulphur hexafluoride, liquid, at plant	Operation EV	600	40002	7,9E-08	kg
transmission network, electricity, high voltage	Operation EV	3666	40002	8,4E-09	km
transmission network, long-distance	Operation EV	3668	40002	3,2E-10	km
operation, lorry 16-32t, EURO5/ RER/ vkm	Operation truck	2732	40003	1,0E+00	vkm
electricity, medium voltage, production UCTE, at grid /UCTE	EOL cars	1002	50001	8,6E+01	kWh
electricity, low voltage, production UCTE, at grid /UCTE	EOL cars	969	50001	3,2E+02	kWh
electricity, medium voltage, production UCTE, at grid /UCTE	EOL trucks	1002	50002	1,7E+02	kWh
electricity, low voltage, production UCTE, at grid /UCTE	EOL trucks	969	50002	6,5E+02	kWh

B.2 Foreground Processes

				A_{ff}										
Full Name	**Process ID**	y_f	**Unit**	**Road-based transport system**	**ICEV assembly**	**EV assembly**	**Truck assembly**	**Body structure car**	**Body structure truck**	**Operation ICEV**	**Operation EV**	**Operation truck**	**EOL cars**
Road-based transport system	10001	1	p										
ICEV assembly	20001		p	700									
EV assembly	20002		p	700									
Truck assembly	20003		p	5									
Body structure car	30001		p		1	1							
Body structure truck	30002		p				1						
Operation ICEV	40001		km	2,8E+08									
Operation EV	40002		kWh	5,2E+07									
Operation truck	40003		vkm	3,0E+07									
EOL cars	50001		p	1400									
EOL trucks	50002		p	5									

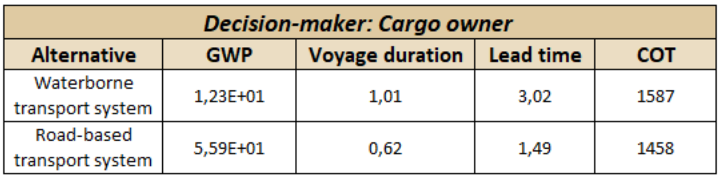
Appendix C

Final input used in multi-objective optimization model



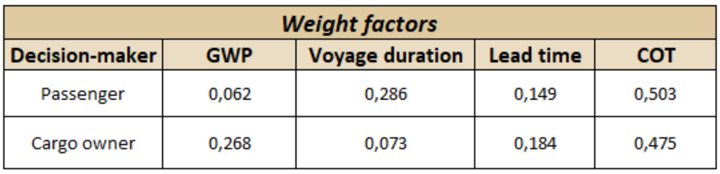
Decision-maker: Commuting worker

Alternative	GWP	Voyage duration	Lead time	COT
Waterborne transport system	7,29E-01	0,24	0,33	49
Road-based transport system	6,69E+00	0,83	0,50	60



Decision-maker: Cargo owner

Alternative	GWP	Voyage duration	Lead time	COT
Waterborne transport system	1,23E+01	1,01	3,02	1587
Road-based transport system	5,59E+01	0,62	1,49	1458



Weight factors

Decision-maker	GWP	Voyage duration	Lead time	COT
Passenger	0,062	0,286	0,149	0,503
Cargo owner	0,268	0,073	0,184	0,475

Tiril Amundsen

NTNU
Kunnskap for en bedre verden