Elias Ødegaard

Decision Support for The Optimal Placement of Battery Swapping Stations for High Speed Passenger Vessels

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

Master's thesis

NTNU
Norwegian University of Science and Technology
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Master's Thesis in Marine Systems Design

Stud. techn. Elias Ødegaard

"Decision Support for The Optimal Placement of Battery Swapping Stations for High Speed Passenger Vessels"

Spring 2022

Background
Domestic voyages with high speed passenger vessels are one of the worst emitters of climate gases per distance unit per person in Norway as of today. The Norwegian counties, which are responsible for the high speed passenger vessel services, are believed to come up with strict demands in the upcoming tender processes. The development of zero emission solutions for this segment of vessels will hence be important both in a Norwegian context, and as a potential export product.

Overall aim and focus
The overall aim of the master's thesis is to develop an optimization model for the placement of battery swapping stations for zero emission high speed passenger vessel routes.

The candidate should presumably cover the following main points:

1. *Provide an overview of the current status and important development trends related to zero-emission high speed vessels.*
2. *Perform a literature review on state-of-the-art battery and battery swapping technology, and present key concepts within decision support for the maritime domain.*
3. *Develop an optimization model for the optimal placement of battery swapping stations on a route.*
4. *Carry out a case study on existing routes relevant for zero emission propulsion and assess the applicability of the results, using the developed optimization model.*
5. *Discuss and conclude.*

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

Professor Stein Ove Erikstad

Preface

This thesis constitutes the completion of my five years of studying Marine Technology at the Norwegian University of Science and Technology. The thesis was conducted during the spring semester of 2022. The scope of the thesis is 30 credits which corresponds to the workload of a full semester.

I would like to thank my supervisor, Professor Stein Ove Erikstad, for valuable guidance and help throughout the semester. I would also like to thank my co-students specializing in Marine System Design for interesting and valuable discussions regarding our theses.

Elias Ødegaard

June 9, 2022

Summary

The maritime industry and the public transportation sector are both taking steps towards a zero emission future. With high speed passenger vessels being one of the worst emitters of climate gases within the public transportation segment, the counties responsible for these services are considering requiring zero emissions in the coming tender processes. Several of the counties have come together to fund a concept development project, and there are several schemes one can apply for, that incentivize the development of zero emission technology and concepts.

Based on the need for innovative zero emission solutions, this thesis focus on battery electric propelled vessels with the possibility of swapping battery modules quickly in port. The thesis aims to develop an optimization model for decision support on the placement of the battery swapping stations, and on deciding how many battery modules a vessel will need at each stop where such a station is established on a given route.

The literature review is conducted in two parts, where the first part presents an overview of technology-related literature. The review includes battery technology specific for marine applications as well as battery swapping technology. An overview of high speed passenger vessel concepts designed specifically for zero emission propulsion is also given. The second part of the literature review introduces ship design theory and a review on decision support in the maritime domain.

To demonstrate the model´s applicability, a case study based on the high speed passenger services in the Oslofjord is performed. For the case, the data input to the model is based on the existing vessels operating in the Oslofjord. The results show that it is possible to establish a battery swapping system for all of the current services. It also reveals the importance of focusing on energy efficiency in designing vessels for such a system.

The case study confirms that the model works as intended and produces realistic and meaningful results for the placement of the battery swapping station, given the input to the model.

Sammendrag

Både de maritime næringene og offentlig transportsektor sikter seg inn på en fremtid med lavere og til slutt null utslipp fra deres operasjoner. Med hurtigbåter som en av de største bidragsyterene til klimagassutslipp fra offentlig transport, har fylkene som er ansvarlig for disse tjenestene begynt å se på muligheten for å kreve null utslipp fra fartøyene i de kommende anbudsprosessene. Flere av fylkene har gått sammen og finansiert et konseptutviklingsprosjekt, og det finnes flere støtteordninger satt opp for stimulere til utvikling av nullutslippsteknologi.

Basert på behovet for innovative nullutslippsløsninger fokuserer denne oppgaven på batteridrevne hurtigbåter med modulære batterier med mulighet for å bytte batterimodulene raskt, i havn. Denne masteroppgaven har som mål å utvikle en optimeringsmodell for beslutningsstøtte til plassering av batteribyttestasjoner og antall batterimoduler som suppleres til et skip i en hver havn en slik stasjon blir etablert.

Literaturstudiet er gjort i to deler, hvor den første delen tar for seg teknologirelatert literatur. Dette inkluderer batteriteknologi spesifikt for marine applikasjoner samt batteribytteteknologi og et overblikk over hurtigbåtkonsepter designet spesielt med tanke på nulltuslipps fremdriftssystemer. Den andre delen av literaturstudiet gir en introduksjon til skipsdesignteori samt en gjennomgang av planlegging og typer operasjoner innenfor maritim transport.

For å demonstrere anvendeligheten til modellen utføres en case-studie basert på hurtigbåtrutene i Oslofjorden. Data-input til modellen er basert på de eksisterende fartøyene som opererer disse rutene i dag. Resultatene fra case-studien viser at det er mulig å etablere et slikt batteribyttesystem på alle de eksisterende rutene i Oslofjorden. Resultatene avslører også viktigheten av å fokusere på energieffektivitet i design av fartøy for et slikt system.

Case-studien bekrefter at modellen virker som planlagt og leverer realsitiske resultat for plassering av batteribyttestasjoner gitt inputen til modellen.

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Abbreviations

IMO	=	International Maritime Organization
GHG	=	Greenhouse Gas
NM	=	nautical mile(s)
AIS	=	Automatic Identification System
NMC	=	Nickel Manganese Cobalt Oxide
LPF	=	Lithium Iron Phosphate
LTO	=	LIthium Titanate Oxide
LP	=	Linear Programming
IP	=	Integer Programming
MILP	=	Mixed Integer Linear Programming
NP	=	Nonlinear Programming
BIP	=	Binary Integer Programming
MWh	=	Mega Watt Hours
kWh	=	Kilo Watt Hours
DWT	=	Deadweight Tonnage
DOD	=	Depth of Discharge
OPEX	=	Operational Expenditures
CAPEX	=	Capital Expenditures
NOK	=	Norwegian Kroner

Chapter 1

Introduction

1.1 Motivation

The International Maritime Organization (IMO) aims to reduce the Greenhouse Gases (GHGs) from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008-levels. Specifically for CO_2-emissions, the goal is to reduce emissions by 40% by 2030 and pursue 70% by 2050 compared to 2008 (IMO, 2018). The Norwegian Government supports the IMO goals and will also provide a framework that enables the Norwegian maritime industry to acquire experience and expertise to be in a good position to be an important supplier for the upcoming restructuring of the global shipping sector (The Norwegian Government, 2019).

Norway has already shown that they are at the forefront of developing environmentally friendly maritime technology. From 2019 to 2021, the number of ferry berths with infrastructure for charging has quadrupled. The number has gone from 15 to 61, and by the end of 2024, there will be 47 more (Almaas, 2021). This shows the rapid conversion of the ferry segment from the first electric ferry was introduced in 2015 until today (Ship-Technology, 2021). There are currently no binding emission targets specifically for the Norwegian maritime sector. The Government of Norway has, however, stated that the plan is that all public transport shall be without emissions within 2025. This includes both ferries and high speed passenger vessels (The Norwegian Government, 2019). Norway is also legally bound to become a low emission society by 2050 through the Climate Change Act, which specifies that the target means a reduction of emission of greenhouse gases in the order of 80-95% compared with 1990 (The Norwegian Government, 2019).

All of the zero emission ferries in Norway today use batteries as their primary power source. Battery technology is however challenging to use for journeys over longer distances, and alternative solutions for zero emission propulsion are needed. There is not yet much proven zero emission technology for maritime use, but the development of such technology is moving forward. One of the presented solutions that have gained traction lately is the concept of using modular batteries that can be swapped for freshly charged ones in port, thus eliminating the need for using valuable time on recharging a vessel's battery.

There is a significant focus on electrifying public transportation, and both the EU and Norway grant large sums of money to different zero emission projects. One of the receivers of such a grant from the Norwegian Enova scheme is Rygerelektra. This is a battery electric vessel with a range of 50 nautical miles (NM), carrying tourists from Stavanger to the fjords within the city (Baird, 2020). The shipowner claims to save 270 000 liters of diesel per year on Rygerfjord being electric. Another Stavanger-based project receiving grants from the EU-project TRAM is the battery electric high speed passenger vessel Medstraum (TrAM-project, 2021). This vessel was recently launched and will soon commence the service to the islands around Stavanger, emission free. Presented here are two examples that there is both will and money to back up innovative solutions for zero emission high speed passenger vessel technology.

Introducing new technology is always challenging. In addition to costly new technology on the vessels themselves, the quay facilities need to be adapted to the demands of the new vessels. The county of Trøndelag and ten other counties did in 2017 finance a concept development project where different consortia delivered concepts for zero emission high speed passenger vessels and the needed infrastructure(Trøndelag Fylkeskommune, 2019). This was stage one of five planned stages leading up to 2-4 finished vessels with different designs. Stage two of the project was recently started, which is a design phase where the goal is to provide new and ready-to-build designs through a competition ending in the first half of 2023 (Trøndelag fylkeskommune, 2021). This shows the forward-leaning attitude of some of the counties behind the upcoming tender processes and shows that Norway is a leading player in financing the development of zero emission maritime technology. When the technology is ready to be introduced to the market, it can also open up for introducing new high speed passenger vessel services as it can compete against more traditional land-based public transport on emissions and time.

1.2 Objective and Purpose of this Master's Thesis

The overall aim of this master's thesis is to develop an optimization model for decision support on where to establish battery swapping stations, and how many battery modules a vessel should take on at such station, for any given high speed passenger vessel service that has the potential to be electrified using a vessel with modular and swappable batteries. Today, these services are provided by diesel-propelled vessels with large emissions. To establish a viable alternative to these vessels, it is crucial to consider the building of the vessels for the specific route in conjunction with the placement of refueling facilities and choice of fuel or power technology. The literature review presented in chapter 3 suggest that battery as a service can be applied to other battery-powered services than electric vehicles, and shows that battery swapping technology is being developed for the maritime domain. The literature review also shows that while both battery swapping and the placement of chargers for electric vehicles have been studied, little to no research has been conducted on swappable batteries for the maritime domain, and on the joint study of the placement of battery swapping stations and battery supply to the vessel servicing the route specifically. In-depth assessments of specific routes was also mentioned by Sundvor et al. (2021) as important for assessing the viability of zero emission high speed passenger vessels.

The optimization model will be applied to a case using the already established high speed passenger vessel services in the Oslofjord as a basis.

1.3 Structure of the Thesis

The current chapter provides a background for the importance of switching the fleet of high speed passenger vessels to zero emission propulsion, as well as the objective and background of this master's thesis. Chapter 2 provides background information on the situation of the high speed passenger vessels in Norway and in the Oslofjord. The plan for zero emission propulsion and possible expansion of the services in the near future is also presented. Chapter 3 and chapter 4 provides a literature review, investigating relevant literature for high speed passenger vessels in general, technological challenges, battery swapping technology and relevant maritime problems. Included in chapter 3 is also a presentation of some relevant vessel concepts that may be suited for this type of operation. In chapter 5, a methodology for developing the optimization problem formulation, and relevant optimization problems are presented. The mathematical formulation and notation for the problem are presented in chapter 6, before the problem definition for the case study and solving of the case are presented in chapter 7. Chapter 8 and chapter 9 contains the discussion and the conclusion, respectively.

Chapter 2

Background

2.1 High Speed Passenger Vessel Services in Norway

Domestic voyages with high speed vessels are today one of the worst emitters of climate gases per kilometer per person in Norway. According to research from the Institute of Transport Economics (Fridstrøm and Alfsen, 2014) it is approximately four times worse than the domestic airline industry, with emissions of 904 grams of CO_2 per personkilometer whereas the domestic airline industry emits 198 grams of CO_2 per personkilometer. This makes the segment an important place to reduce emissions, transitioning to a low carbon society. As a high-tech, high-cost country, developing zero emission technology and concepts will also benefit Norwegian workers, shipyards, and design offices exporting this technology and these vessels out in the world (Innovasjon Norge, 2021). As this segment of vessels becomes greener and cities continue to grow, it may also be a viable solution for expanding public transport in populated areas. Compared to other means of public transport, seaborn transportation is highly flexible and will be easy to move from one location to another. It is also relatively quick to produce and to get ready for service compared to a tram or a train service. It will, on the other side, not be able to serve as many people as land-based transportation running on tracks, and being zero emission, the vessels will have some distance limitations. However, the vessels can still be a good supplement to the already existing public transport in growing cities located by water, such as New York and Oslo.

There are currently 73 high speed passenger vessels operating in Norway today (Sundvor et al., 2021), excluding the smaller vessels not required to use Automatic Identification System (AIS). Most of these operate on the west coast and north in the country, as presented in Figure 2.1, and the few vessels in the Oslofjord are typical commuter services that operate two or three voyages on a route in the morning and in the afternoon. With the focus from the government on cutting emissions through developing new green technology, a lot of money has also followed through different public support schemes (The Norwegian Government, 2019). The owner of the routes, the counties, are through this incentivized to acquire zero emission vessels to operate their routes.

Figure 2.1: Visualization of AIS data from the 73 high speed passenger vessel routes identified by Sundvor et al. (2021).

2.2 High Speed Passenger Vessels in The Oslofjord Area

The high speed passenger vessels in the Oslofjord of today are to be renewed before 2024. The tender process leading up to choosing the operator of the final contract will soon commence. In connection with this, Ruter AS, the company responsible for public transportation in the Oslo area, made a report mapping the possibilities and consequences of requiring zero emission vessels. Their goal is that all the public transportation shall be zero emission within 2028. In the report named Mapping of Possibilities and Consequences (Ruter, 2020), the company found that the services are popular as a commuting service, and that the users of especially the commuter services feel connected to the services and will not readily accept changes to the schedule. The report concludes that it is viable to demand zero emission vessels from 2024. Ruter AS will also consider an expansion of the services in the near future.

The location of jobs is an important factor in the demand for transportation in an area. In Oslo, there are several clusters where companies are located, like Lysaker, Fornebu, Aker brygge, and Skøyen. Bukholm et al. (2017) finds that the number of people living in Asker, Hurum, and Røyken, the three municipalities on the west side of the Oslofjord, was 90 000 in 2017. Figure 2.3 shows substantial population growth, especially in the area Røyken, which includes Slemmestad, where one of the current ports is located. The number of commuters from the towns along the west side of the Oslofjord is presented in Figure 2.2. The transportation options from these regions towards Oslo are today car, train, bus or by boat. Depending on where one lives, the choice of transport mode will vary as people consider factors like cost, travel time, convenience, and comfort in their choice of transportation method. Establishing good public transportation can contribute to an increase in the value of the area. Bukholm et al. (2017) describes the situation on the roads leading into Oslo as bad, with congestion on the roads leading to relatively large traffic delays. This affects both the car and the bus traffic. Upgrading the existing high speed passenger vessel network can be a part of solving the congestion problem leading people over to other means of transportation. Exploring the option to extend the routes, an as flexible zero emission transportation system as possible is desirable. The current high speed passenger vessel route arrives at Aker brygge, but as Figure 2.2 shows, people living in the inner part of the Oslofjord also work at Fornebu/Lysaker. Expanding the public transportation service can also lay grounds for more significant growth than expected in areas along the fjord. The passenger base for the high speed passenger vessel services in the area is considerable.

Arbeidskommune	Antall arbeidstakere	Prosent
Hurum	1 795	39 %
Oslo	558	12 %
Røyken	402	9 %
Asker	371	8 %
Drammen	364	8 %
Bærum	258	6 %

Arbeidskommune	Antall arbeidstakere	Prosent
Røyken	2 762	25 %
Oslo	2 145	19 %
Asker	1 939	17 %
Bærum	1 348	12 %
Drammen	1 050	9 %
Hurum	225	2 %

Arbeidskommune	Antall arbeidstakere	Prosent
Asker (hele kommunen)	5 779	40 %
Oslo	4 471	31 %
Bærum	2 866	20 %
Drammen	463	3 %
Røyken	279	2 %

Figure 2.2: Commuters from respectively Hurum, Røyken and Asker and their work place (Bukholm et al., 2017).

2.3 Concluding Remarks

This chapter shows the importance of the high speed passenger vessel services in Norway and especially in the Oslofjord. It also presents the possibility of expanding the services based on number of commuters and population growth in the area

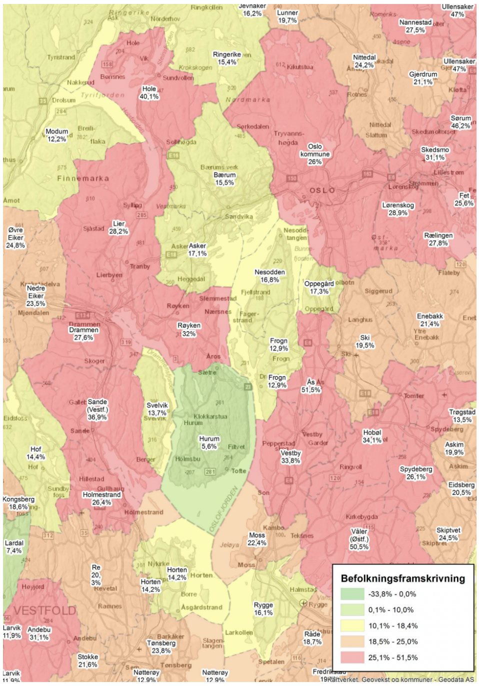

Figure 2.3: Expected population growth around the Oslofjord towards 2036 (Bukholm et al., 2017).

are the Oslofjord. As many of the existing services are commuter services, the importance of following the established schedule is obvious. Switching to zero emission propulsion for high speed passenger vessels thus calls for a vessel and system able to quickly replenish the vessels with energy.

Chapter 3

Literature Review Technology

In this and the next chapter, a presentation of literature relevant for the objective of this thesis will be presented. This chapter includes general literature on high speed passenger vessels, battery and battery swapping technology, and an overview of some promising high speed passenger vessel concepts.

3.1 High Speed Passenger Vessels in General

IMO (2000) defines a high speed craft as a craft capable of maximum speed equal to or exceeding $3.7\nabla^{0.1667}$ in meters per second, where ∇ is the displacement corresponding to the design waterline. For domestic shipping, the Norwegian Maritime Authority defines high speed crafts as vessels with a length (L) equal to or more than 24 meters and capable of a maximum speed equal to or exceeding 20 knots. High speed crafts can thus include everything from smaller passenger vessels in sheltered water to large ocean crossing Ro-Ro vessels. The remaining parts of this chapter focus on the smaller high speed crafts suitable for battery electric propulsion, excluding the large ocean crossing vessels. The vessels will be referred to as high speed passenger vessels.

Wang and McOwan (2000) identifies different high speed craft hull designs and briefly discusses the advantages and disadvantages of the different designs. The vessels identified were monohulls, catamarans, hovercrafts, surface effect ships, and hydrofoils. Catamarans were identified as the market leaders, with twice as many catamarans as any other high speed crafts being built in 1995 and 1996. Catamarans are still the preferred hull shape for today's high speed passenger vessel owners. The advantages catamarans have over the other vessels were pointed out to be their stability, high maneuverability, and relatively low resistance through the water. Negative sides of the catamaran were mentioned to be its lack off ability to carry a large payload and its slamming movements in rougher sea leading to discomfort amongst the passengers.

The era for high speed passenger vessels in Norway was kicked off in 1960 with a hydrofoil vessel imported from Italy (Foss, 1989). After some years of troubling with much downtime for the hydrofoil vessels, the catamaran became a favorite along the Norwegian coast. The number of high speed passenger vessel services has steadily increased over the years, and there are today 73 different high speed passenger vessel routes identifiable by AIS data (Sundvor et al., 2021).

Sundvor et al. (2021) did a study of all high speed passenger vessels in Norway, identifying the vessels suitable for hydrogen and battery-electric propulsion. Using AIS data together with modeled energy consumption and assuming a maximum battery weight or maximum compressed hydrogen volume each vessel can carry, they found 51 of the identified routes suitable for hydrogen propulsion and 12 of the routes suitable for battery-electric propulsion. As this study was done on a large scale, with a general model for most of the vessels' energy consumption, the individual routes' results must be handled with care. The authors also acknowledged that looking into specific routes and making small changes could alter the individual routes' results. Looking at other zero emission technologies such as battery swapping could also alter the outcome, as charging time at each of the stops on the routes examined was a limiting factor ruling out battery propulsion for several of the routes.

3.1.1 Battery Technology

Chen and Sen (2016) states that battery technology has evolved rapidly over the last years. The technology went from lead batteries to lithium-ion based battery technology with higher energy density, longer cycle life, and lower self-discharging rate. Papanikolaou (2020) identifies Nickel Manganese Cobalt Oxide(NMC), Lithium Iron Phosphate(LFP), and Lithium Titanate Oxide(LTO) as the most common types of batteries used in the maritime domain. For high speed vessels, the specific gravimetric and volumetric energy density needs to be as high as possible due to space and weight limitations (Papanikolaou, 2020). Lithium battery technology with a specific energy of 250 Wh/kg is available on the market (Dsoke et al., 2015). However, battery safety is essential for marine applications, and LTO technology is known to have superior thermal stability but offer a lower capacity of 50 - 70 Wh/kg (Wu and Bucknall, 2016). The previous mentioned together with the recharging rate are essential considerations to take into account when choosing battery technology. A battery technology that can substantially increase both gravimetric and volumetric energy densities as well as removing safety issues like leaking is Solid State Batteries (Sousa et al., 2013). Solid State Batteries are often pointed to as the next big development within battery technology, and Kartini and Genardy (2020) finds research on solid electrolytes to be growing fast due to safety reasons. The paper also predicts solid state batteries to replace the current commercial lithium-ion batteries based on liquid electrolytes. Lithium-sulfur technology is one of the solid state technologies predicted to improve both gravimetric and volumetric energy densities and lower the price, extending the lifetime of the batteries and avoiding thermal runaway (tu.no, 2022). Due to that sulphur is easily available in large quanta, the cost related to the cathode will be 1% of the cost of a NMC-cathode. According to Zheng et al. (2021) it is however still a big challenge to achieve large-scale applications of lithium-sulphur batteries.

Papanikolaou (2020) presents and discusses some of the technical challenges for zero emission battery propelled high speed marine vessels. The specific issues pointed to on the technical side are the low lightship weight, battery technology, hull form optimization, and charging technology. Low lightship weight is vital for all high speed vessels to achieve low resistance and thus lower fuel consumption. For zero emission battery propelled vessels, the additional weight of the batteries will make up a larger portion of the lightship weight. For the battery technology, Papanikolaou (2020) identifies battery capacity, battery weight and space requirements, charging frequency, and battery life as important issues to deal with in the design of such a vessel. Hull form optimization for minimum powering at specified service speed with multiple constraints for fitting batteries, motors, and safety systems are also pointed out as important issues to handle in the design process. On the operational side, the study points to time scheduling and the decisions related to charging spots, charging frequencies and charging time as key issues to solve. The study also compares a conventional catamaran with a battery propelled catamaran and finds that a conventional catamaran has a range of more than double that of a battery-electric catamaran while simultaneously operating with a 50 % higher speed. It is however pointed to that also the marine battery technology is rapidly improving towards better solutions with higher capacity, better energy efficiency, and longer lifetimes. This is also supported by Verma and Kumar (2021) which writes about developments in the energy storage systems for the marine environment. Some of the technologies mentioned as promising are lithium-sulfur, Thin Plate Pure Lead, and Lithium Manganese batteries.

3.1.2 Battery Swapping Technology

In the car manufacturing industry, which has come further than the maritime industry in implementing electric propulsion systems and operates at a much larger scale, battery swapping stations have already been launched. The Chinese car company NIO launched battery as a service in August 2020 (NIO, 2020), and continues to expand its network of battery swapping stations. Jain et al. (2020) researched the benefits of building battery swapping stations for electric vehicles from different points of view. From the owner of the vehicles point of view, the cost of the vehicle, the short swapping time, and saved time traveling over larger distances were identified as benefits. For the station owner, benefits of a swapping station were identified to be reduced electricity costs as the process of charging can be forecasted, that less parking space is needed, that the cost of batteries will decrease with rapid development of battery technology, and that the charging process will become easy as the batteries are produced according to a given standard. An advantage for the power grid is that the batteries can be charged in off-peak hours, thus avoiding problems with capacity in the grid. Tahara et al. (2020) points to some of the major challenges for electric vehicle deployment to be the prohibitive battery cost and the large amount of time required for energy replenishment. The paper also suggests that battery as a service could be applicable to other battery-powered services than electric vehicles.

Danese et al. (2022) identifies some of the challenges of establishing battery swapping stations to be the absence of a standard battery interface among the producers of electric vehicles. The cost compared to a regular charging station is also highlighted as a disadvantage. On the other hand, it is pointed out that battery swapping can be better suitable for a fleet of vehicles.

In the maritime domain, battery swapping technology is just getting started. The vessel Alphenaar had its maiden voyage in September of 2021. This is the first electric inland vessel in the Netherlands, and transports beer for Heineken on the canal between Alphen aan den Rijn and Moerdijk. Two twenty-foot containers store 45 battery packs each which power the vessel. The vessel can swap out the two containers in 15 minutes when arriving in port with low battery power (Zero Emission Services, 2021; Lewis, 2021). The project recently received further funding from the government, leading to the development of 75 battery containers, 14 battery swapping stations, and 45 electrified inland vessels (Berry). The American startup FleetZero is also in the business of electrifying vessels with batteries stored in modular twenty-foot containers. They plan to retrofit already existing vessels with battery-electric propulsion while at the same time develop a battery-electric vessel for trans pacific cargo delivery (electrive.com, 2022; fleetzero.com).

The company Shift is offering modular batteries in a smaller pod size, suitable for smaller type vessels (shift-cleanenergy.com/, 2022). What all these solutions have in common are that they are pay-as-you-go solutions where one pays for the use and do not have to deal with maintenance and other tasks and costs one usually would have to care for as the owner of the battery.

In Norway, the ferry and high speed passenger vessel company, Norled is together with SEAM AS, developing a battery swap concept for high speed passenger vessels. As this vessel segment is to become zero emission, Norled believes that a battery swapping system is the best solution for the vessels to maintain high speed and regularity without major upgrades to the power grid. Publicly released information about the project states that a vessel with two modules will be able to sustain a speed of 35 knots in 30 minutes or 30 knots in 45 minutes. This corresponds to a range of 8.75 NM per module at 35 knots and 11.25 NM per module at 30 knots. One might assume that this will vary broadly depending on the size and design of the vessel. The system, which is patent-pending under the name Autonomous Battery Swap, is illustrated in Figure 3.1.

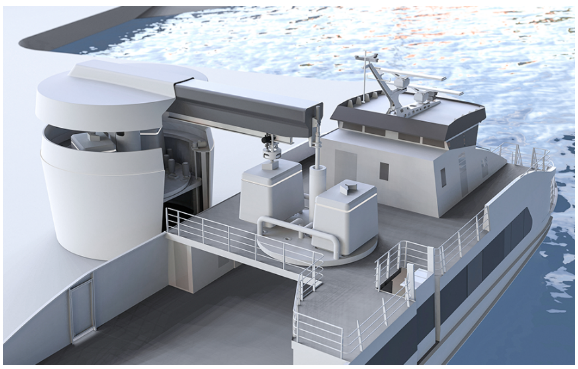

Figure 3.1: Battery swapping system developed by Norled and SEAM (seam.no, 2022).

3.2 An Overview of Relevant Vessel Concepts

This section will present some of the promising high speed passenger vessels still at the concept stage. Parts of this section is influenced by the specialization project leading up to this master´s thesis.

As mentioned in chapter 1, in 2017, multiple Norwegian counties came together and financed a concept development project where different consortia used their expertise to deliver concepts for zero emission high speed passenger vessels. The project's goal is to end up with two to four finished vessels with different designs. One of the designs' requirements is that it can reach speeds over 30 knots. Stage two of the project was recently started and is supposed to lead to ready-to-build concepts before the first half of 2023. This chapter will primarily focus on the vessels presented through this project.

Before looking into the vessels of the future, the two already existing vessels Rygerelektra and Medstraum deserve a mention. With a top speed of 20 knots, Rygerelektra delivered in 2020, is technically not a high speed craft. It is, however similar in both appearance and behavior. The battery is the largest installed on a high speed passenger vessel today, with a capacity of 2100kWh, stated to have a range of 50 NM (Baird, 2020). Rygerelektra can accommodate up to 300 passengers. Medstraum, which can accommodate up to 150 passengers, has a service speed of 23 knots and is thus classified and approved as a high speed craft. It's battery package has a capacity of 1500kWh, stated to have a range of 23 NM.


Figure 3.2: Rygerelektra and Medstraum (Baird, 2020; E24.no, 2022)

3.2.1 Catamarans

The catamaran has been the number one choice of hull form for high speed passenger vessels along the Norwegian coast since the 1980s. The latest considerable innovation in this segment came in the early 2000s when Brødrene Aa., a Norwegian yard specializing in the production of catamarans, started constructing hulls with a lightweight carbon fiber sandwich technology. Brødrene Aa. continues focusing on energy-efficient hull forms and has launched a concept called AERO which is claimed to reduce the energy consumption by 10% from today's vessels (Brødrene Aa., 2019). Though still a concept, Brødrene Aa claims the concept to be ready for application and production and to fit for both battery-electric and hydrogen propulsion.

Figure 3.3: AERO40 by Brødrene Aa. (2019).

3.2.2 Foiling Vessels

After no foiling vessels being active in Norwegian waters since the late 1980s, multiple actors are now working on concepts utilizing hydrofoils as a resistance-reducing measure. Two of the vessels still taking part in the concept development project mentioned above are foiling vessels. The concept ZeFF, consists of a trimaran hull with deep-submerged hydrofoils. The deep submerged hydrofoils are to be controlled by a control system actively controlling flaps on the foils. For propulsion of the vessel, pods are to be directly connected to the aft foils.

Figure 3.4: ZeFF by LMG marine and partners (LMG Marin, 2022).

The other concept utilizing foils to reduce resistance is quite different. The consortia led by Transportutvikling AS have developed a concept vessel using passive foils lifting the hull partially out of the water. A sophisticated control system is thus not needed as the vessel is self-stabilized. In the design of this vessel, a system with modular batteries based on a floating battery swapping terminal was also looked into and considered a good option. Advantages with this system are mentioned to be the short time for swapping modules compared to conventional fast charging, that the cycle life of the battery modules will be greater than on a battery that is fast charged, and that the load on the local power grid will be lower (Transportutvikling AS, 2022).

Figure 3.5: Concept vessel by Transportutvikling and partners (Transportutvikling AS, 2022).

3.2.3 Surface Effect Ships

A surface effect ship (SES), as the name suggests, reduces the resistance from the water by utilizing the surface effect. A traditional surface effect ship has a twin-hull like a catamaran and a rubber skirt in the bow and the stern to enclose the space between the double hull. Air is then pumped into this space to lift the vessel partly out of the water, creating a surface effect, and thus reducing the resistance from the water.

ESNA, which has previous experience building SES for the offshore wind industry, presents a classic SES with a range of 43 NM and a service speed of 40 knots, functioning as traditional SES. The other SES is presented by the company SES-X which has developed a new hull form. The hull is a flat bottomed single hull with a hollowed-out pocket stretching over the length of the hull. At speed, the pocket is pumped full of air, thus creating a lubricating air pocket between the hull and the water, reducing the resistance from the water. SES-X has a functioning battery-electric prototype vessel, and ESNA has previously delivered a diesel-electric SES for the offshore wind industry.

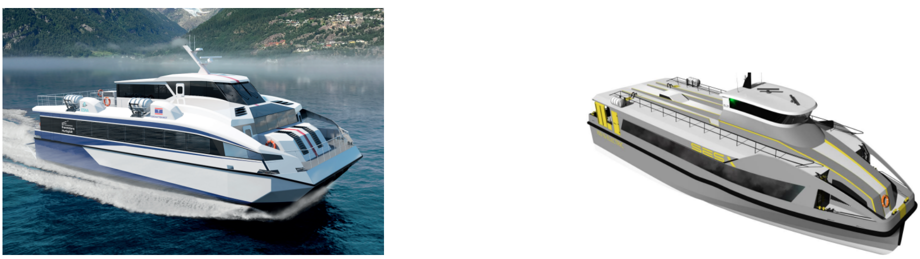

Figure 3.6: SES from ESNA and SES-X, respectively (ESNA; SES-X, 2022).

Chapter 4

Literature Review Decision Support

This chapter provides a literature review of decision support relevant literature in maritime transportation, a presentation of basic network types for maritime transportation, and ship design theory.

4.1 Modes of Transportation in Maritime Transportation

Lawrence (1972) distinguishes between three separate modes of transportation in shipping. The three modes are industrial shipping, tramp shipping, and liner shipping. Industrial shipping is characterized by a ship, or fleet of ships, that must ship a total demand contracted while minimizing costs. There are usually no fixed routes, and the routes change based on the contracted cargo. A contract could span over several years or be limited to fewer or even one voyage. Decisions that have to be made in industrial shipping are routing and scheduling decisions. Tramp shipping is similar to industrial shipping but does also have the opportunity to take on spot cargoes. Decisions will then, in addition to routing and scheduling, include the selection of spot cargoes. The objective of tramp shipping problems is to maximize the revenue by taking on spot cargoes while at the same time meeting the contractual obligations with the customer that has signed the contract spanning over a longer period. Liner shipping is characterized by ships that follow a schedule on a given route, similar to a bus route, stopping regularly in given ports at given times over a given period.

Although the classifications described above were developed for large ocean going vessels, such as container and bulk ships, High speed passenger vessel services are similar to liner shipping, as the high speed passenger vessels are to follow a predetermined route that follows a published schedule.

4.2 Planning Levels

Shipping problems are often divided into three different planning levels. Christiansen et al. (2007) define these as the strategic planning level, spanning over years, the tactical planning level, spanning from one week up to a year, and the operational planning level, spanning from a day up to a week. The strategic planning level typically includes market and trade selection, fleet size and mix decisions, and network design decisions. Christiansen et al. (2007) identifies the challenges in liner shipping to be quite different from industrial and tramp shipping on all planning levels. Liner shipping serves the demand of many customers at the same time with it's predetermined routes and frequency. Industrial and tramp shipping is on the other hand serving either one, or a few customers, who control the ships. Thus, the route is not predetermined with a given frequency as for liner shipping. High speed passenger vessel services can be compared to liner shipping as there are several similarities in the way of operating predetermined routes with a given frequency. Meng et al. (2014) presents planning levels specifically for liner shipping. A short presentation of the planning levels and decisions to be made under each planning level is presented in Figure 4.1.

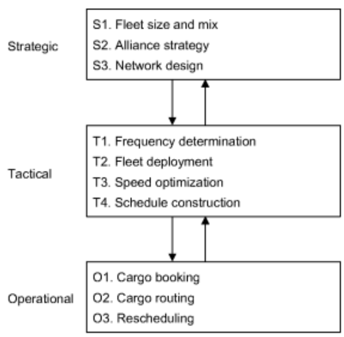

Figure 4.1: Planning levels in liner shipping according to Meng et al. (2014).

Deciding the fleet size and mix is one of the main strategic issues for shipping companies and ship owners. This involves deciding on what type of ships to include in the fleet, their sizes and the number of ships of each size (Christiansen et al., 2007). Another important aspect of strategic planning is the network design, often referred to as a network design problem (Christiansen et al., 2013). The selection of routes is, in a general matter, important for both port selection and visit frequency. In the case of routing high speed passenger vessels, where time is a critical factor for the customers, the selection of routes will also play a prominent role in which order ports shall be visited. Alliances and cooperation between liner shipping competitors are common (Meng et al., 2014). Alliance strategy will, however, not be discussed here as it is not directly relevant for an operator of a high speed passenger service.

On the tactical level, fleet deployment, frequency determination, speed optimization, schedule construction, and other tactical decisions are made (Meng et al., 2014). These decisions cannot be seen as isolated decisions and are intertwined with both the strategic and the operational decisions. As an example, tactical decisions play a large role in network design. The different problems should therefore not be investigated in isolation. Scheduling is an important part of creating a reliable service for the customer. The schedule for high speed passenger vessels is often divided into seasons as the customer base may vary a lot from season to season. The frequency will also differ on different weekdays as the demand for transportation may vary throughout the week. Fleet deployment is closely linked to the fleet size and mix problem and the scheduling problem as it is about assigning ships to routes. Both the number of vessels on a route and the number of ports included in a route decide the frequency the customers can be offered on a route. According to Abioye et al. (2019) there are approximately 400 liner services worldwide, with most of them having a weekly service. For a high speed passenger vessel service, the frequency will normally be substantially higher.

At the operational level, the short-term decisions are made. For traditional liner shipping, this includes speed optimization, as bunker costs can constitute up to 75% of the total operating cost of a containership Ronen (2011). It also includes cargo routing, which is how cargo should be transported across routes from an origin port to a destination port. Container routing problems are usually formulated as Linear Programming (LP) models where the number of containers is treated as a continuous decision variable (Meng et al., 2014). If needed, the passengers in a high speed passenger vessel service problem can also be treated as a continuous decision variable as passengers are pretty much homogeneous as a group. Rescheduling of vessels is short-term decisions based on external factors during the voyage. Examples can be bad weather or engine trouble. In traditional liner shipping, these problems are often resolved by increasing speed or delaying the delivery of cargo (Meng et al., 2014). On the short legs of high speed passenger vessel routes, it may not be possible to catch up the delay with increased speed. In tender specifications, there is therefore often a requirement that when an arrival is delayed, the operator of the vessels gets a fine and/or has to be responsible for getting the customers to their final destination if they lost connecting transportation.

4.3 Network Design

Christiansen et al. (2020) identifies several types of liner shipping services based on the structure of the service. A simple or cyclic service visits each port in the service exactly once. Nodes or ports visited more than once in a service are called butterfly nodes. A service with one such node is called a butterfly service. If all the nodes are visited twice in the service, it is defined as a pendulum service. The services are defined as complex if any node is visited multiple times. Examples of the different service types are presented in Figure 4.2 and Figure 4.3

Figure 4.2: Cyclic service and butterfly service (Christiansen et al., 2020).

Figure 4.3: Pendulum service and complex service (Christiansen et al., 2020).

4.4 Relevant Ship Design Theory

On the strategic level, the fleet size and mix is an important long-term decision. To get the optimal fleet size and mix, it is essential to design the correct type of vessel, or vessels, for the fleet. This section presents basic design theory specifically for ship design.

Pahl et al. (2007) points to the importance of a systematic process doing engineering design. One of the most well-known systematic methodologies within ship design is the design spiral. The design spiral captures the sequential, iterative nature of the design process and presents a smooth process of balancing conflicting requirements (Andrews and Erikstad, 2015). The classic design spiral can be described in four phases. The first iteration in the loop is the concept design, the second to fourth iteration is the preliminary design, the fifth iteration is the contract design, and the sixth and last iteration is the detailed design, according to Papanikolaou (2014). Papanikolaou (2014) also describes the iterations in the design spiral to include the following:

- **Concept design** - Owner´s requirements are translated into technical ship characteristics. This stage corresponds to a feasibility study, where alternative designs are explored. Preliminary estimations of basic ship dimensions are made.
- **Preliminary design** - In this step, an accurate determination of the ship's main characteristics is established. This should satisfy the owner's requirements and forms the basis for the compilation of the shipbuilding contract.
- **Contract design** - Necessary calculations and drawings are completed in this stage. This includes a detailed description of hull form, the exact estimation of powering needed to achieve the specified speed from the contract, analysis of ships behavior in waves and its maneuvering properties, and more.
- **Detailed design** - A detailed design of everything important on the ship is done. This includes all structural elements and the setup of technical specifications for the construction and fitting of equipment.

This way of doing ship design can be identified as a point-based engineering design method, often starting out by altering one or several known designs and iterating through the spiral to a satisfactory result is achieved (Singer et al., 2009).

Levander (2012) points out that the spiral model quickly locks the designer to his first assumptions, which will be patched and repaired on instead of generating independent alternatives. Based on these limitations to the spiral model, Levander developed a new method for ship design.

Levander (2012) states that a ship must perform a variety of functions, which all can be described as individual systems that are integrated into a ship. By defining each system and identifying the performance requirements for the individual

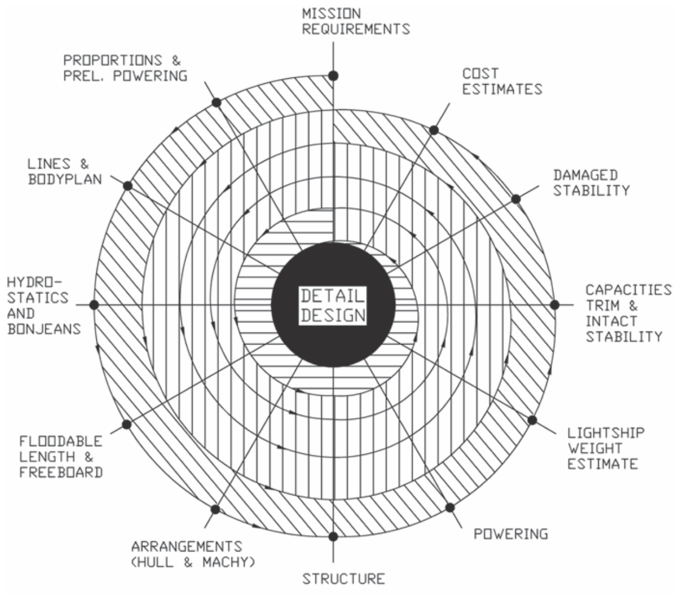

Figure 4.4: The design spiral (Robert Taggart, 1980).

systems, a framework for ship design is developed. This framework is named System Based Ship Design and Levander (2012) explains that by adding simple algorithms, many design calculations related to the systems that make up the ship can be performed by computer. This frees up time the designer can spend on improving and evaluating the design. Designing, using the System Based Ship Design approach, the specification of main characteristics is postponed until a quite balanced solution is proposed (Andrews and Erikstad, 2015).

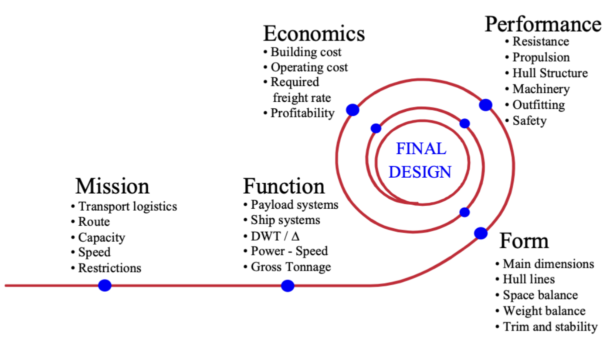

Figure 4.5: The System Based Ship Design process (Levander, 2012).

Another and newer design method for marine systems and ships is the holistic approach. This approach is based on multi-objective multi-disciplinary optimization and aspires to find the optimal ship with respect to the whole life cycle of the ship. Instead of the design spiral, the holistic approach to ship design uses a design synthesis model. The steps in the design spiral are thus parallel processed, often by different software tools. According to Papanikolaou (2019) the advantage of this approach is that it explores a greater range of design options than the traditional iterative design process in the preliminary and contract design phase. On the other side, performance criteria to evaluate the different resulting ship designs are needed. This might be hard to evaluate for innovative new designs due to uncertainties related to the performance of systems or modules. The holistic approach is systemic and considers the ship's systems to be modular, where a module may be replaced by other modules over the ship's life cycle. A holistic ship design method can be identified as a set-based engineering design method as a wide range of designs are parallel processed (Singer et al., 2009).

4.5 Placement of Charging Stations

No studies have been conducted on the placement of charging stations for the maritime domain specifically. There have however been conducted several different studies on the placement of charging infrastructure for electric vehicles in transportation networks. Danese et al. (2022) performs a review study of the planning of high-power charging stations for electric vehicles. Among the findings were that many of the reviewed studies optimized the allocation of the charging stations based on costs. Some also used multi-objective optimization strategies to consider all actors involved. User cost, charging time, distance, and other factors are handled differently in the reviewed studies. A variety of solution methods are also identified in the studies. Of metaheuristic methods, binary lightning and ant colony are mentioned, while among the deterministic methods, nonlinear programming (NP), mixed integer linear programming (MILP) and integer linear programming (IP) are mentioned.

Fredriksson et al. (2019) presents a practical approach to optimally allocate charging stations in large-scale transportation networks. The approach uses an iterative approximation technique, where the IP problem is solved by using a probabilistic random walk route selection. The focus of the model is to reach the maximum coverage with the minimum number of charging stations.

Phonrattanasak and Leeprechanon (2014) proposes an optimization model for the placement of fast charging stations, aiming to optimally place the charging stations in areas with dense traffic for the minimum total cost of the stations and the minimum total loss of distribution network. The problem was solved using ant colony optimization, and the study found the results with this method to find the best location of the fast charging stations.

Chapter 5

Methodology

This chapter describes the methodology used to develop the optimization model for decision support. First, operations research and optimization will be introduced before more relevant, specific optimization problems and methods will be presented.

5.1 Operations Research and Optimization

Hillier and Lieberman (2013) states that as the name suggests, operations research involves ”research on operations” and identifies operations research to be applied to problems that concern how to, within organizations, conduct, and coordinate operations. The type of organization is unimportant, and operations research has been applied in many areas. A characteristic of operations research is that it searches for an optimal solution for the model that represents the problem at hand by resolving conflicting interests among the components in an organization. The major phases of an operations research study are defined by Hillier and Lieberman (2013) to be:

1. Define the problem and gather relevant data.
2. Represent the problem through a mathematical model.
3. Develop a computer-based procedure for deriving solutions to the problem from the model.
4. Test and refine the model as needed.
5. Prepare for the ongoing application of the model as prescribed by management.

6. Implement.

Hillier and Lieberman (2013) also emphasize the importance of using a team approach as large operations research studies require everything from mathematicians and statisticians to economists, computer scientists, and engineers.

Martins and Ning (2021) describes optimization as the concept of finding the best possible solution by changing variables that can be controlled. These variables are often subject to a number of constraints. The considered aspects of a problem must be quantifiable such that the optimal value can be found by changing the mentioned variables. The objective function of an optimization problem can either be maximized or minimized, dependent on the goals of the problem. Typical optimization problems can be within operations research, finance, and transport and logistics. Typical objectives are to maximize revenue or minimize a problem's cost or travel time. Optimization can thus be seen as a subfield of, or tool for performing operations research.

Martins and Ning (2021) also emphasize the importance of being methodical in formulating the optimization problem and suggests the approach shown in Figure 5.1. As a real-world problem is to be described mathematically, the problem will have to be somewhat simplified. This leads to a trade-off between an exact description of the problem and the ability to solve the problem. It is especially important to understand the limits of the simplified problem. Martins and Ning (2021) also point out that developing the mathematical model has the added benefit that it helps the designer better understand the problem at hand.

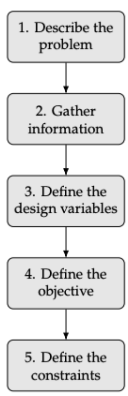

Figure 5.1: Steps in optimization problem formulation (Martins and Ning, 2021).

Following the approach in Figure 5.1, the first step is to describe the problem with words. This step does not require any optimization and can be a vague description. The goal of the step is to describe the system and state the goals and requirements. The second step is to acquire as much information as possible about the problem. All the possible inputs and outputs should be identified, and their limitations should be understood. Information gathering is an iterative process throughout all the steps in the problem formulation. Further, the design variables need to be decided. These are the variables that will be decided by solving the problem, thus describing the optimal solution. The design variables can be either continuous, binary, integer, or discrete. Defining the objective function is important for the intended output. It does not matter how accurate the mathematical modeling and its solution is, if it is not representing the intents of the system. The final step is to add constraints to the problem, which are functions to limit the design variables.

Optimization problems can be categorized in many different ways. One way to categorize them is to split them into linear and non-linear optimization problems. The optimization process in this thesis is done with linear programming, which will be in focus throughout the rest of this chapter. Hu and Kahng (2016) defines a linear program as the maximization or minimization of a linear function subject to linear constraints. A linear function invites to logical thinking and provides insight into the problem, and is easier to solve as there exist efficient algorithms for solving the problem. A linear formulation should therefore be striven for if possible. Hu and Kahng (2016) points to one of the disadvantages of linear programming to be that assuming a linear problem is not always realistic and can limit the model. A linear optimization problem can again be split into different categories. Dependent on the definition of the variables and the constraints in the linear optimization model, the model is typically described as Linear Programming (LP), Integer Programming(IP), or Mixed Integer Linear Programming(MILP). Linear programming is the term used for all linear formulations of an optimization problem. Integer Programming is a linear optimization problem, where the variables are further constrained to only take integer values. Under integer programming, one can also identify binary integer programming(BIP), where the variables are strictly binary. Mixed integer programming is a combination of the above, where certain variables are continuous, and others can be integer or binary.

5.2 Network Programming

Many of the systems that surround us in society today can be represented through networks. The roads and other transportation systems, computer systems, the electrical grid, and molecular networks are just some of the examples that can be represented as networks. Many network optimization models are special types of linear programming. The setup, terminology, and some specific network optimization problems will be briefly described here.

Hillier and Lieberman (2013) describes a network to consist of a set of points and a set of lines, where the points are referred to as nodes or vertices and the lines as arcs or edges. The arc between two nodes may have a flow through it, and if the flow only is allowed one way, it is called a directed arc. An arrow indicates the direction at the end of the arc. A network with only directed arcs is called a directed network. If two nodes are connected through a sequence of distinct arcs, this is called a path. A path can also be either directed or undirected. A connected network is a network where every pair of nodes is connected through a path.

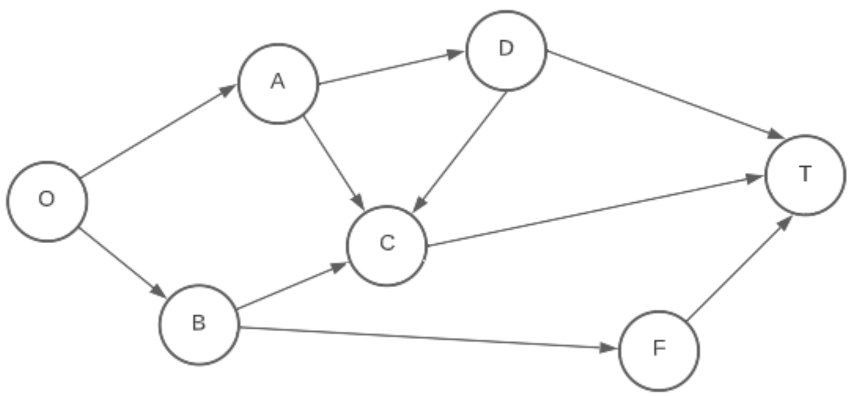

Figure 5.2: An example of a connected and directed network.

5.2.1 Shortest Path Problem

The shortest path problem is a well-known problem within network optimization. The objective of the problem is to find the weight of the shortest path between a given start node and a given end node in a network. The problem's extensive applicability in everything from road networks (Ehmke et al., 2016) packet routing (Krioukov et al., 2004), disease-gene associations, (Goh et al., 2007) and much more has made it a well-researched topic within different research communities. Typical objectives to optimize in shortest path problem studies are minimization of expected distance or travel time, minimization of expected carbon emission, and other values that can be represented as a value on the arc between the vertices in the network.

Most shortest path problems are special variants of LP, IP or MILP-problems, but can be solved more efficiently by specialized algorithms. Rachmawati and Gustin (2020) looks into two of the most used algorithms for routing and road networks, Dijkstra's algorithm and the A* algorithm. The researchers find the algorithms to have almost the same performances on town or regional sized problems, while A* performs better solving a large-scale map problem. Most commercial solver does however use the famous simplex method in some form. The simplex method was developed by Georg Dantzig in 1947 (Dantzig, 1990). Hillier and Lieberman (2013) describes the simplex method as a algebraic procedure, with a geometric underlying concept. They also point to that the simplex method is widely available for computer systems through code, and can solve very large linear programs. Another well known method is the column generation method, which is especially efficient for solving large problems.

5.2.2 Minimum Cost Flow Problem

The shortest path problem is a special case of the more general structured minimum cost flow problem (Hillier and Lieberman, 2013). Like the shortest path problem, the minimum cost flow problem considers a cost for flow through an arc. It can also consider multiple supply and destination nodes with associated costs. Using the notation from Hillier and Lieberman (2013), the mathematical formulation of the problem is as presented in Equation 5.1 through Equation 5.4. An explanation of the sets, parameters, and variables follows in Table 5.1, Table 5.2 and Table 5.3. Prerequisites for the model are that the set N includes at least one supply and at least one demand node and that the network is connected and directed.

Set	**Definition**
N	Stops, indexed by i and j

Table 5.1: Set for the minimum cost flow problem.

The value of b_i is dependent on the node i. If node i is a supply node, $b_i > 0$, if i is a demand node, $b_i < 0$, and if i is a transshipment node, $b_i = 0$.

$$min \sum_{i \epsilon N} \sum_{j \epsilon N} c_{ij} \cdot x_{ij} \tag{5.1}$$

subject to:

Parameter	Definition
c_{ij}	Cost per unit flow through arc between i and j
u_{ij}	Arc capacity for arc between i and j
b_i	Net flow generated at node i

Table 5.2: Parameters for the minimum cost flow problem.

Variable	Definition
x_{ij}	Flow through arc between i and j

Table 5.3: Variable for the minimum cost flow problem.

$$\sum_{j \epsilon N} x_{ij} - \sum_{j \epsilon N} x_{ji} = b_i \qquad \forall i \in N \tag{5.2}$$

$$0 \leq x_{ij} \leq u_{ij} \qquad \forall i, j \in N \tag{5.3}$$

$$\sum_{i \epsilon N} b_i = 0 \qquad \forall i \in N \tag{5.4}$$

The objective function in equation 5.1 minimizes the cost of the path through the network. The constraint presented in equation 5.2 ensures that the flow in and out of a node is consistent for each type of node b_i. The constraint presented in equation 5.3 secures that the flow through each arc is less or equal to the allowed flow for that arc, and the constraint in equation 5.4 is often added to ensure that the problem has a feasible solution. The constraint ensures that the number of supply and demand nodes are equal.

Chapter 6

The Battery Swapping Problem

It is crucial to continue serving the people and the communities reliant on high speed passenger vessel services all over Norway when moving towards a low carbon society. The vessels on the current services are burning marine diesel oil, and counties all over Norway are looking into demanding zero emission solutions for propulsion in the next tender process. Operating fully with zero emission in the near future requires a well-established network of zero emission refueling technology, developed in close collaboration with the development of the vessels servicing the route.

One promising solution for zero emission high speed passenger vessels is vessels with battery-electric propulsion with battery modules that can quickly be swapped out in port for a set of fully charged battery modules. A system like this is expensive, and it is essential to minimize the costs related to both the number of battery modules needed and the number of swapping stations in the battery swapping system.

The optimization model presented in this chapter is constructed as a deterministic model where the input data is to be based on estimated values for the problem being evaluated. The model is designed to be a tool to provide decision support in the process of placing battery swapping stations and deciding the number of battery modules needed to be supplied to a given vessel at each swapping station to reach the next swapping station. A predefined route with known distances between ports and the known order of port calls is a prerequisite for using this model. The investigation of the optimal solution for the individual routes can again be used as the basis for decision making in developing larger zero emission public transportation systems on water.

Deciding where to establish battery swapping stations and the battery capacity needed between the different swapping stations are decisions playing into all planning levels described in section 4.2. On the strategic level, the placement of the stations will affect the possibility of expanding to serve more routes as well as the fleet size and mix, which will depend on the battery capacity needed between the stations. On the tactical level, fleet deployment and the schedule construction which is closely linked to the fleet size and mix, are affected. On the operational level, the ability to reschedule a service will be linked to the placement of swapping stations and the needed battery capacity between the stations.

The optimization model presented below is advised to be used as a part of an iterative design procedure. The battery modules' capacity, weight, and size, have an immediate effect on the vessel's design related to space requirements, sizing, and displacement, and thus also the speed and required power for the vessel. With these contradicting requirements, Papanikolaou (2020) suggests an iterative design procedure for deciding the characteristics of the system. Acquiring more knowledge about the above described contradicting requirements and their relations, the model may also be possible to implement in a holistic design approach.

6.1 Model Description

Battery swapping stations can be established in every stop i along the route. The vessel can in each stop, either go to the next without swapping battery modules or swap the battery modules for a number of new battery modules from the set B consisting of different numbers of battery modules. There is a cost connected to establishing the battery swapping station in each port and a cost connected to how many battery modules that is taken on board in each of the ports. The battery swapping problem can be seen as a variant of a minimum cost flow problem where solving it will find the path with the lowest cost through the network, identifying the ports to establish battery swapping technology in, and deciding the number of battery modules that will be used on the legs between the established stations for a given vessel.

Following the methodology in, chapter 5, the input and output of the optimization model are defined in table 6.1.

Input	Output
Cost of establishing swapping stations	Placement of swapping stations
Distances between ports	Number of batteries swapped out in port
Order of port calls	Cost of the system
Cost of battery module	
Range of battery module	
Number of battery modules a vessel can hold	
Range for vessel per kWh	

Table 6.1: Optimization model input and output. There is no direct relation between input and output on the same line.

6.2 Notation

The notation for the sets, parameters, and variables used in the optimization model are presented in this section.

Set	Definition
N	Stops, indexed by i and j. First and last stop denoted by s and e.
A	All possible directed arcs between i and j for $D_{ij} <= \max\{R_b\}$
B	Number of battery modules b

Table 6.2: Sets used in the optimization model.

The set N consists of the stops on the route. All stops are also potential placements for battery swapping stations. The start and end node in N, s and e, are often geographically identical as the routes start and end in the same spot, but does not have to be. The set A holds all possible directed arcs between every port i and j. The set B consists of the different numbers of battery modules the vessel on the service can take on.

Parameter	Definition
C_i	Cost of establishing battery swapping station in port i
C_b	Cost of leasing b battery modules
D_{ij}	Distance between port i and j
R_b	Range for b battery modules

Table 6.3: Parameters used in the optimization model.

An important aspect to remember, which might not be straightforward, is to relate the costs to each other in a realistic manner to represent the true relations of the costs. This is important as the cost heavily affects the decision on where to establish stations and the number of battery modules to take on.

Variables	Definition
x_{ij}	1 if arc between i and j is included in the cheapest path solution
y_{ib}	1 if b batteries are taken on in port i in the cheapest path solution
u_i	1 if a battery swapping station is established in node i
w_{ij}	Represents the product of x_{ij} and u_i for linearization of constraint

Table 6.4: Variables used in the optimization model.

6.3 Mathematical formulation

The objective function is presented in equation (6.1), with the constraints following in (6.2) through equation (6.11), which will be further described below. The model is constructed as a BIP problem, where all the variables are restricted to hold the value 0 or 1.

$$min \sum_{i\epsilon N} C_i \cdot u_i + \sum_{i\epsilon N} \sum_{b\epsilon B} y_{ib} * C_b \tag{6.1}$$

Subject to:

$$w_{ij} - x_{ij} = 0 \qquad \forall (i,j) \in A \tag{6.2}$$

$$w_{ij} \leq x_{ij} \qquad \forall (i,j) \in A \tag{6.3}$$

$$w_{ij} \leq u_i \qquad \forall (i,j) \in A \tag{6.4}$$

$$w_{ij} \geq x_{ij} + u_i - 1 \qquad \forall (i,j) \in A \tag{6.5}$$

$$\sum_{j\epsilon N} x_{sj} = 1 \qquad \forall i \in N \tag{6.6}$$

$$\sum_{i\epsilon N} x_{ie} = 1 \qquad \forall j \in N \tag{6.7}$$

$$\sum_{i \epsilon N} x_{ij} - \sum_{i \epsilon N} x_{ji} = 0 \qquad \forall j \in N \backslash \{s, e\} \tag{6.8}$$

$$\sum_{b \epsilon B} y_{ib} \cdot R_b \geq x_{ij} \cdot D_{ij} \qquad \forall (i, j) \in A \tag{6.9}$$

$$\sum_{b \epsilon B} y_{ib} \leq 1 \tag{6.10}$$

$$u_i, x_{ij}, y_{ib}, w_{ij} \in \{0, 1\} \tag{6.11}$$

The objective function presented in equation (6.1) minimizes the cost of establishing battery swapping stations in the ports, while the second part minimizes the total cost of the battery modules supplied to the vessel throughout the route, over all the ports.

The first four constraints, equation (6.2) to equation (6.5), are the linearization of the non-linear constraint presented in equation (6.12), which secures that a battery swapping station is established in the stops that are included in the optimal solution. The linearization is done by replacing the product of x_{ij} and u_i with the new variable w_{ij}. The new variable then replaces each occurrence of $x_{ij} \cdot u_i$ in the constraints. For the model above, equation (6.12) is rewritten to equation (6.2). x_{ij} and/or u_i = 0 implies that w_{ij} must be equal to zero. This is ensured through equation (6.3) and equation (6.4). Equation (6.5) forces w_{ij} to be 1 when the product of x_{ij} and u_i equals 1, which only happens if both variables are equal to 1.

$$x_{ij}(u_i - 1) = 0 \qquad \forall (i, j) \in A \tag{6.12}$$

The constraint in equation (6.6) ensures that only one of the arcs going from the start node can be included in the solution path. Equation (6.7) has the same function for the end node, ensuring that only one of the arcs going to the end node can be included in the solution path. Together with the flow conservation constraint (6.8), the two equations ensure a continuous path through the network from the start node to the end node. These constraints can be recognized from equation (5.2) in the minimum cost flow problem.

Equation (6.9) makes sure that the number of battery modules taken on in node i can provide the vessel with the range to reach the next node where a battery swapping station is established. Equation (6.10) ensures that only one number of battery modules is taken on in each port, and equation (6.11) are binary constraints securing the variables to bed binary.

6.4 Input to the Model

The structure of the input to the model is described and illustrated in this section.

The parameters that need to be established before solving the problem is mentioned in Table 6.3. With the distances, costs, and ranges decided, the sets in Table 6.2 can be established. The set B, along with the range R_b for b number of battery modules, is specific for different vessels, while the other parameters and sets are specific for each different route the battery swapping problem is applied to.

A service going from a given start port through a set of stops to an end port is indexed in the set N with the number corresponding to the stop on the route, with the starting point indexed as 0. Figure 6.1 illustrates the indexation of the ports for a simple round trip.

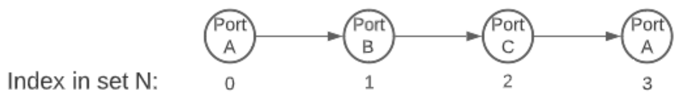

Figure 6.1: Indexation of the set N for a round trip.

The set A is generated by identifying all the directed arcs between i and j. This is illustrated in Figure 6.2. The distance D is defined such that the distance between stop 0 and 3 is equal to the distance between stops 0 and 3 through stops 1 and 2. Thus, choosing the path from node 0 to node 3 will not exclude stops 1 and 2 on the physical route. To not make the problem larger than it needs to be, the directed arcs between i and j that have a greater distance than the range the largest number of battery modules available can provide, is not generated. The objective of the problem is to find the cheapest path through the network based on where to place battery swapping facilities, and the number of batteries supplied to the vessel in each port, not the physical shortest path as the shortest path problem would.

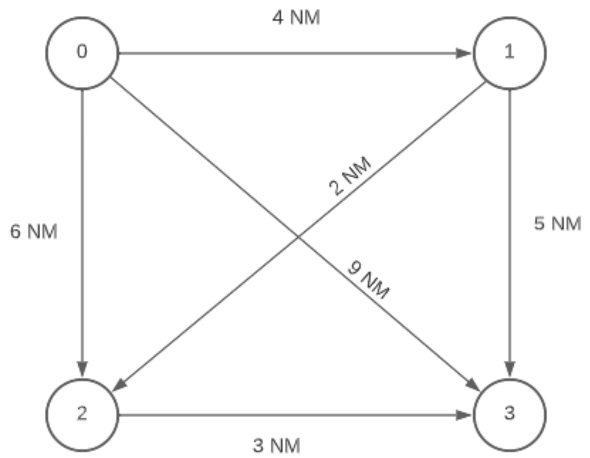

Figure 6.2: Visualization of the network representation of a simple route.

stops	**0**	**1**	**2**	**3**
0	0	4	6	9
1	4	0	2	5
2	6	2	0	3
3	9	5	3	0

Table 6.5: Distance matrix for network in Figure 6.2. All values in NM.

6.5 Additional Constraints for Special Cases of Services

As presented above, the indexing of the nodes are done such that a stop on the route is equal to a node in the network. This way, a route with two or several stops in the same port will have a different index for the same port on the different stops. A pendulum service going from port A to port D through port B and C and then back to port A through port C and B will be indexed in the set N as presented in Figure 6.3. A cyclic service, doing several rounds back to back on the route, will be indexed as presented in Figure 6.4.

For other services than a service going from A to B and a cyclic service doing one voyage from a port back to the same port, additional constraints are added to connect the nodes that's index represent the same port. For a pendulum service, equation (6.13) is added. The constraint is set up to ensure that a battery swapping station established in stop i is also established in the stop representing the same port on the way back. For a cyclic service going back to back several times, equa-

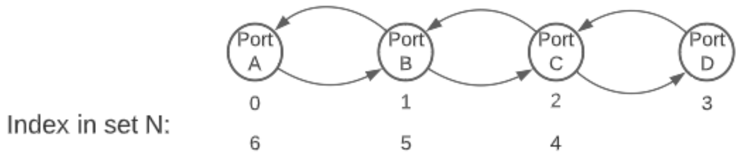

Figure 6.3: Indexation of the set N for a pendulum service.

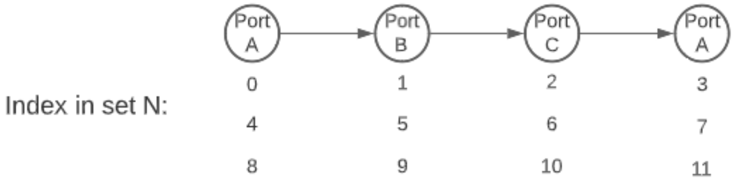

Figure 6.4: Indexation of the set N for a cyclic service with three cycles.

tion (6.14) is added. For a butterfly service or a complex service, the stops that's index represent the same port will have to be paired manually by constraining the variables representing the stops that represent the same port, or ports, under consideration to be equal. This setup counts the cost of establishing a battery swapping station as many times as the port where it is established is represented by different stops. The cost of establishing one swapping station in a port should therefore be divided on the number of stops that represent the same port, which together sums up to the cost of establishing one station.

$$u_i - u_{e-i} = 0 \qquad \forall i \in N \tag{6.13}$$

Where e is the last node in the set N.

$$u_i - u_{i+\frac{|N|}{S}} = 0 \qquad \forall i \in F \tag{6.14}$$

Where S is the number of cycles in the cyclic service, and F is a subset of N containing the first $N - \frac{|N|}{S}$ nodes in N.

6.6 Modifications to Model to fit Fixed Battery Vessel

By doing some changes, the model can be fitted to optimize where charging stations for a vessel with fixed battery electric propulsion should be located, as well as the needed capacity for the battery on board. The most important modification is the introduction of a continuous variable deciding the capacity of the battery based on the largest distance between two ports with charging facilities. Notation for the modified model is presented in Table 6.6, Table 6.7, and Table 6.8. Swapping stations are redefined as charging stations for this model.

Set	Definition
N	Stops, indexed by i and j
A	All possible arcs between i and j for $D_{ij} <= \max\{R\}$

Table 6.6: Sets used in the modified optimization model.

The set B is removed from the original model, as the objective is no longer to decide between the number of batteries in the set but the size of one permanent battery.

Parameter	Definition
C_i	Cost of establishing charging station in port i
C_k	Cost per nautical mile the battery can power the vessel
D_{ij}	Distance between port i and j
R	Maximum range the battery can propel the vessel

Table 6.7: Parameters used in the modified optimization model.

From the original model, the range parameter is changed to be a parameter holding the maximum range the fixed battery can provide. The cost per battery is also swapped out for a cost per range.

Variables	Definition
x_{ij}	1 if arc between i and j is included in the cheapest path solution
u_i	1 if a charging station is established in node i
w_{ij}	Represents the product of x_{ij} and u_i for linearization of constraint
k	Continuous variable deciding the battery capacity

Table 6.8: Variables used in the modified optimization model.

The objective function presented in equation (6.15) will now minimize the cost of establishing charging stations in the first part of the equation and minimize the cost of the stationary battery in the second part of the equation.

$$min \sum_{i \epsilon N} C_i \cdot u_i + k * C_k \tag{6.15}$$

$$k \geq x_{ij} \cdot D_{ij} \qquad \forall (i,j) \in A \tag{6.16}$$

The flow conservation constraints and the linearization constraints remain the same. The constraint in equation (6.9) is adapted to fit a fixed battery, and is presented in equation (6.16). This constraint ensures that the battery capacity is large enough to move the vessel the distance between ports where charging is to be established. Implementing it like this, only the largest distance between two charging ports will constrict the model. The constraint from equation (6.10) is removed for this modification as it is no longer needed.

6.7 Assumptions

The models presented in this chapter are based on a range of assumptions about the vessel, and the operating context the vessel is performing in that should be kept in mind when using the model. The model is designed to be used on existing routes or to assess alternative planned routes. The battery swapping model does not take time into account, thus always assuming that the timetable is possible to follow, regardless of the number of battery modules loaded and unloaded in each port. It is assumed that if a battery swapping station is established, it can supply as many battery modules as needed to the visiting vessel. A linear connection between the number of battery modules and the range of the vessel is also assumed. The additional resistance from the extra battery modules due to increased weight is thus not accounted for. This is assumed as it is hard to predict the added resistance from one battery module, as the relation between weight and resistance is not linear. On cyclic and pendulum routes, the vessel might be able to service the route with fewer battery modules in total than the model predicts. On a cyclic service, swapping modules in the same port on every round, two sets of battery modules could be enough given that they would be possible to recharge between every cycle. The same would be the case for a pendulum service where the battery modules could be swapped out in the same port both back and forth. The cost for the number of battery modules taken on board does not consider this as a pay-per-use or pay-as-you-go financial model is the norm of the already existing battery swapping services. For the fixed battery case, the charging time and cost of this is not accounted for, as this would call for a dynamic programming approach. The fixed battery case can thus not be assumed to be able to keep up with established timetables for services and is not directly comparable to the battery swapping case.

Chapter 7

Case Study

Ruter, the public transportation company in Oslo, and the owner of the high speed passenger vessel services in the Oslofjord is looking into requiring zero emission propulsion in the coming tender process for their services presented in Figure 7.1. The ferry services B1, B2, and B10 are already converted to battery-electric propulsion. It is essential with a high speed passenger vessel service that is quick and reliable while simultaneously satisfying the strict environmental demands of the future. Operating fully with zero emissions from 2024, when the winner of the tender process is set to take over the operation of the routes, requires a well-established network of zero emission refueling technology. The placement of these facilities is vital for an as cost-effective transportation system as possible. This case will address the placement of battery swapping stations using the model defined in chapter 6, for each of the individual high speed passenger vessel services in the Oslofjord.

In the design of a new vessel with modular batteries and battery swapping technology, the battery system will be an important part of the design process. The batteries' weight, space requirements, and placement have an immediate effect on the vessels' displacement, stability, and size and thus also on the installed power and maximum speed. This calls for an iterative design procedure (Papanikolaou, 2020). It is thus reasonable to use the existing vessels on the services today as a starting point for the design of the vessel taking over the services. In a process like this it is important to look at the system as a whole and design both the vessels and the infrastructure around the vessels in conjunction and through multiple iterations. The case below will present results for the first iteration in such a design process, investigating three different types of vessels with two different types of battery modules compared to the same vessels with a fixed battery package.

Figure 7.1: High speed passenger vessel services in green and yellow (ruter.no, 2021).

All cases are solved with the solver Gurobi (Gurobi Optimization, LLC, 2022) implemented in python using the Gurobi python API, gurobipy. To show how the model was implemented in Gurobi the python scripts applied to the routes can be found in the attachments to this thesis.

7.1 Case Specific Data

In an area with high speed passenger vessel services, there are often several different routes serviced by the same vessels at different times. As seen in Figure 7.1, the services B21 and B22 are only operated in the summer. Looking into the schedule of the services, it is noted that the services B20 and B11 are both commuter services with a long break from service mid-day. All the routes could probably be serviced by two vessels, but a backup vessel is required as it is costly not to fulfill the demands from the tender process. Three different vessels will thus be used in the case study. The data specific for the case is presented in this section.

The distances used in the case-study are approximate as they were established with measurements from the NAIS-tool(nais.kystverket.no) from the Norwegian Coastal Administration.

7.1.1 Battery Swapping

Specific details about the power consumption of new vessels are well-guarded company secrets that are hard to get hold of. The vessels operating in the Oslofjord as of now are Baronen, Baronessen, and Tidevind. Information from Sea-web Ships will be used to derive the energy demand for the vessels. Although a battery swapping system will require new vessels specifically designed for the services, for the case below, all routes will be optimized individually using the vessels servicing the routes today as reference vessels. This will present different optimal solutions for different sizes of vessels and will contribute to highlighting important aspects to consider when designing both the battery swapping system and the vessels for the service.

As presented in subsection 3.1.2, a few different solutions for modular batteries for the maritime domain are being developed. The different providers operate with different sizes, capacities, and weights for their batteries. fleetzero.com claims their battery will weigh 8 tonnes with a capacity of 2 MWh, have the length and width of a 20ft container, and a height of 1.5 meters. The system has received approval for vessel propulsion from the American Bureau of Shipping (electrive.com, 2022). Zero Emission Services (2021), which already have batteries in operation, provides battery modules with a capacity of 2 MWh but contained in a full-size 20ft container. Shift Clean Energy with its PwrSwäp, which is approved by Bureau Veritas, claims a weight of 3 tonnes for their pod with a capacity of 280 kWh (shift-cleanenergy.com/, 2022). The first battery-electric high speed passenger vessel, Medstraum, is being built with a capacity of 1.5 MWh with a battery weight of 12 tonnes. Battery modules of 500kWh each thus seem like a reasonable and realistic assumption. The battery modules will, throughout the chapter, be referred to as battery modules, batteries, or simply modules.

Vessel	Power Demand [kW]	Service Speed [kn]	DWT [t]	PAX
Baronen	1836	30	28	250
Baronessen	1273	30	22	180
Tidevind	1498	30	19	147

Table 7.1: Power output from machinery for maintaining the service speed of the vessels today.

Studying the potential for battery-electric propulsion on all of the Norwegian high speed passenger vessel services, Sundvor et al. (2021) sets the maximum allowed depth of discharge (DOD) to 60%. This is due to that a safety margin is needed in addition to that a large DOD will accelerate the aging of the battery, shortening its lifetime (Ecker et al., 2014). This case study will use a maximum allowed DOD of 80%, as the batteries are changeable and considerably cheaper to replace than on a vessel with a fixed battery system. 20% of the capacity is left as a safety margin for unforeseen events and emergency cases, but also to extend the cycle life of the batteries. Sundvor et al. (2021) also operates with a maximum allowed weight for the batteries of 80% of the vessel's dead weight tonnage. Looking at already existing vessels, this is an accessible parameter to use. In this case, it is used to estimate the maximum carrying capacity of batteries for vessels of similar type and size. Sundvor et al. (2021) presented this methodology to several shipbuilders, who agreed that this was a reasonable approach. Based on the Corvus Dolphin Power, a weight of 8kg/kWh is assumed. This corresponds to 4 tonnes per module. With these restrictions, the number of modules and the range of each vessel is found with equation (7.1) and equation (7.2), respectively.

$$\lfloor \frac{DWT[t] \cdot 0.8}{4[t]} \rfloor = no.\, modules \tag{7.1}$$

$$\frac{500[kWh] \cdot 0.80}{power\ demand[kW]} \cdot speed[kn] = range[NM] \tag{7.2}$$

The battery technology is rapidly improving, and batteries are expected to become lighter and cheaper while still providing the same or greater capacity within few years. The case is hence also investigated with a scenario where 500 kWh are available, corresponding to 100% of the battery capacity of today, or representing technical advances with a lighter battery module, corresponding to 80% DOD for a battery module with the capacity of 625 kWh with a specific weight of 6.4 kg/kWh.

Vessel	Modules	400 kWh available	500 kWh available
Baronen	5	6.5	8.2
Baronessen	4	9.4	11.8
Tidevind	3	8.0	10.0

Table 7.2: The maximum number of modules and the range with 400 kWh and 500 kWh available per module.

For the existing and planned battery swapping projects described in subsection 3.1.2, the financial model is set up as a pay-as-you-go or pay-per-use service. Therefore, it will be assumed that an external company will provide the battery service. This includes both establishing the battery swapping stations and providing the battery modules. The cost for the company servicing the routes will be a cost based on where and how many battery stations are to be established, and a cost based on how many battery modules that are taken on at each stop. The cost of the electricity itself is included in the cost to the external company.

The cost will be defined per year and accounted for as a part of the operational expenditures(OPEX), unlike a battery-electric high speed passenger vessel with stationary batteries, which would be a part of the capital expenditures(CAPEX). The objective will be to minimize the contributions to the operator's OPEX from the battery swapping system.

Estimating the cost of establishing a battery swapping station is complex and will be subject to various local restrictions and factors depending on what is needed in each port. The costs are also typically split between stakeholders in the project, for example, the owner of the berth, the operator, and state-funded subsidies for green technology. For this case, the contribution from the operator is assumed to be 15 million NOK per swapping station. It is assumed to be more costly to establish battery swapping stations at the islands in the fjord due to limitations in the power grid and the cost of transporting materials and labor by boat to the islands. The cost of choosing to build a battery swapping station on the islands is therefore set to cost 4 million NOK more, thus totaling 19 million NOK. Building in the smaller ports around the fjord where the berths will have to be improved before establishing a station will also have an additional cost of 2 million NOK, totaling 17 million NOK. To get a cost comparable to the cost of leasing a battery, the cost will be divided into equal installments over ten years.

The cost for leasing a battery is derived from the cost of buying a battery. Battery prices are declining, and different sources estimate costs ranging from 100$ up to 800$ per kWh. ZEM AS, a provider of battery technology for the maritime domain, operates with a price of 225 000 €, corresponding to approximately 2 250 000 Norwegian kroner for a battery system of 500kWh. This will be used as the basis for calculating the lease cost. The yearly payment for a battery is found by splitting the price of a battery minus the residual value over the length of the lease and adding a factor for financing cost. The financing cost is set to 11% of the yearly payment. Assuming a lease running 10 years, equivalent to the lifetime of a battery, the residual cost will be 0 NOK. The result is a yearly payment per battery of approximately 250 000 NOK per year. There will also be a cost for placing more than one battery on board a vessel related to the lost opportunity to carry other goods. This cost will be an additional 50 000 NOK per year per battery module.

Cost Component	Cost [MNOK/year]
Establish battery swapping station	1.5
Establish battery swapping station on an island	1.9
Establish battery swapping station in a small port	1.7
Lease of one battery module	0.25
Lease of two battery modules	0.55
Lease of three battery modules	0.85
Lease of four battery modules	1.15
Lease of five battery modules	1.45

Table 7.3: Cost related to batteries and battery swapping stations.

7.1.2 Fixed Battery

For the fixed battery scenario, the maximum allowed size of the battery is based on the same assumptions as for the battery modules with 400kWh available. A maximum allowed weight for the battery of 80% of the current vessel's DWT and an allowed DOD of 80%. The limitations for the different vessels are presented in Table 7.4.

Vessel	Max weight [tonnes]	Capacity [kWh]	Range [NM]
Baronen	22.4	2800	36.6
Baronessen	17.6	2200	41.5
Tidevind	15.2	1900	30.4

Table 7.4: Maximum allowed weight of the battery, the capacity of the largest allowed battery, and range with such battery.

Knowing that Medstraum can take 150 passengers, has a battery capacity of 1500 kWh, and a range of 23 NM (E24.no, 2022), this seems like reasonable numbers with the vessels being in the same range when it comes to the consumption of kWh per NM. A price of 4500 NOK/kWh is assumed for the fixed battery. The cost of establishing a charging station is set to the same as the cost for establishing the battery swapping. To be able to compare the cost of buying a battery with leasing battery modules, the price of buying a battery is split in equal installments over ten years.

7.2 Route B20

From the timetable presented in Figure 7.2, route B20 can be identified as a regular commuter service with two vessels doing the route twice and thrice back to back, respectively. Both in the morning and then again in the afternoon. It is also noted from the timetable that the route is a cyclic service. This is also confirmed with AIS data from marine traffic over 24 hours. The constraint from equation (6.14) is thus added to ensure that it is beneficial to swap batteries in stops that represent the same port. The set N is indexed as illustrated in Figure 6.4, with three cycles. Starting from Aker Brygge.

Mandag - fredag *Monday - Friday*

	Aker brygge	Slemmestad	Vollen	Aker brygge
x	——	0605	0613	0638
x	——	0640	0648	0713
x	0641	0711	0719	0744
x	——	0745	0753	0818
x	0746	0816	0824	0849

Mandag - fredag *Monday - Friday*

	Aker brygge	Vollen	Slemmestad	Aker brygge
x	1510	1535	1544	1612
s	1545	1610	1617	——
x	1620	1645	1654	1722
x	1655	1720	1729	1757
s	1730	1755	1802	——

Figure 7.2: Morning and afternoon timetable for route B20 (ruter.no, 2022b).

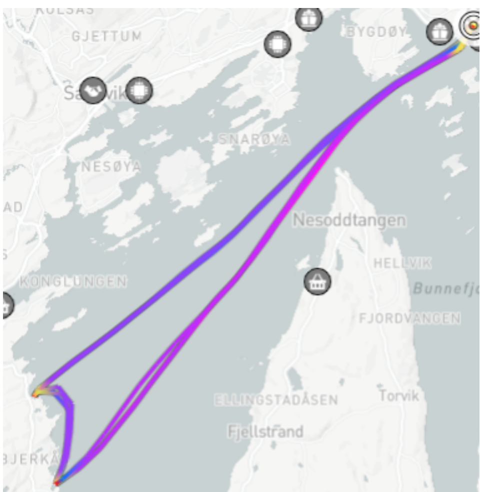

Figure 7.3: AIS-data over 24 hours for route B20 (marinetraffic.com)

7.2.1 Results B20

Solving the problem with Gurobi gives the result presented in Table 7.5, Table 7.6 and Table 7.7 for the different vessels in the different cases. The distance matrix used for route B20 is presented in appendix A.1.

400 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	4	3	3
3	4	3	3
7	4	3	3
Objective value [MNOK/year]	4.95	4.05	4.05

Table 7.5: Results showing optimal solution for B20 with 400kWh available per module.

500 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	3	2	3
3	3	2	3
7	3	2	3
Objective value [MNOK/year]	4.05	3.15	4.05

Table 7.6: Results showing optimal solution for B20 with 500kWh available per module.

Fixed Battery	x = vessel stops to recharge		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	x	x	x
3	x	x	x
7	x	x	x
Objective value [MNOK/year]	2.23	2.02	2.10
Capacity of battery [kWh]	1652	1146	1348

Table 7.7: Results showing optimal solution for B20 with fixed battery.

The results in table 7.5 shows that the optimal solution for route B20 is to establish a battery swapping station in the stops corresponding to Aker Brygge, and then swap out the same amount of batteries on each round. Using a vessel similar to Baronessen or Tidevind is the best option for this route as it can do one full round on three battery modules compared to Baronen, which needs four. This is due to the range limitations per battery as presented in table 7.2. Allowing 500 kWh to be used, as presented in Table 7.6, both Baronen and Baronessen can service the route with one battery module less at each swapping station, reducing the cost of Baronen to the level of Tidevind. The yearly contribution to the OPEX is reduced by 900 000 NOK compared to the scenario where 400 kWh are available. Servicing the route with a vessel with fixed batteries would lead to substantial savings, in the range of up to two million NOK due to savings in battery costs.

7.3 Route B21

Route B21 is the longest of the routes in the Oslofjord basin and is only serviced in the summer. From April to June, it runs only on the weekends, while from June to the end of August, it runs every day, before it until the beginning of October only runs on the weekends again. One entire round trip from Aker Brygge back to Aker Brygge is done in one go every weekday from June to August. On the weekends, two full round trips are performed the whole season. In addition, on Fridays, one extra trip from Aker Brygge to Drøbak and back is serviced the whole season.

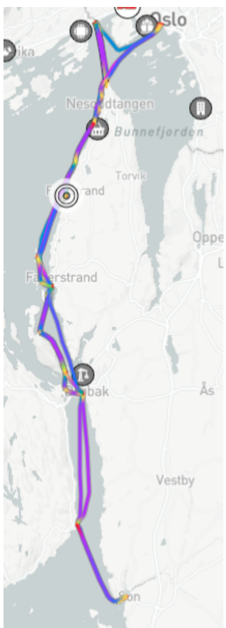

Figure 7.4: AIS-data over 24 hours for route B21 (marinetraffic.com)

Both from the route schedule (ruter.no, 2022c) and from Figure 7.4, route B21 can be identified as a pendulum service. The constraint in equation (6.13) is added to make sure that the model takes into account that establishing battery swapping station in the stops that indexes the same port is beneficial.

Stoppestedsliste

Sone	Stopp	Min	Sone	Stopp	Min
1	Aker brygge	00	2S	Lågøya	55
2S	Nesoddtangen	15	2S	Fagerstrand	60
2S	Flaskebekk	18	2S	Aspond	65
2S	Sjøstrand	21	3V	Håøya	70
2S	Ildjernet	25	3V	Oscarsborg	80
2S	Steilene	32	4V	Drøbak	90
2S	Ommen	35	4V	Filtvet	105
2S	Fjellstrand	40	4V	Son	120
2S	Søndre Langåra	50			

Figure 7.5: Stops on route B21, with time from the start at Aker Brygge (ruter.no, 2022c).

The cost of establishing a battery swapping station follows table 7.3, where the the stops Flaskebekk, Sjøstrand, Ommen, Fjellstrand and Filtvedt are defined as small ports, and the stops Ildjernet, Steilene, Søndre Langåra, Lågøya, Aspond, Håøya and Oscarsborg are located on islands. The distance matrix used for route B21 is presented in appendix A.2. With this in mind, the results for the different scenarios are as presented in Table 7.8, Table 7.9 and Table 7.10.

7.3.1 Results B21

400 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	5	3	3
14	-	-	3
15	-	1	-
16	5	-	-
17	-	3	-
18	-	-	3
Objective value [MNOK/year]	5.9	5.15	5.55

Table 7.8: Results showing optimal solution for B21 with 400kWh available per module.

The number of swapping stations established is limited to one for all the vessels in the scenario presented in Table 7.8. Baronessen and Tidevind have to swap battery modules back and forth, while Baronen only swaps battery modules halfway, in

500 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	2	2	3
10	4	-	-
14	-	2	-
15	-	-	1
17	-	-	3
18	-	2	-
22	2	-	-
Objective value [MNOK/year]	5.25	4.65	5.15

Table 7.9: Results showing optimal solution for B21 with 500kWh available per module.

Fixed Battery	x = vessel stops to charge		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	x	x	x
14	x	x	x
18	x	x	x
Objective value [MNOK/year]	3.7	3.49	3.68
Capacity of battery [kWh]	1572	1090	1283

Table 7.10: Results showing optimal solution for B21 with fixed battery.

the port of Son. The optimal stops to swap modules in for Baronessen are 15 and 17, which both represent the port of Filtvedt. For Tidevind, the cheapest alternative is establishing a swapping station in the port of Drøbak, represented by stops 14 and 18.

Allowing each battery module to discharge 500 kWh, the optimal number of battery modules and placement of the swapping stations are changed for all vessels. The results in Table 7.9 shows that the optimal solution for all of the vessels now are to swap batteries two times after leaving the start node. For all vessels, the swaps are still done in stops that correspond to the same port. Only one battery swapping station is thus needed in all cases. Based on the optimal solution for Baronen, a swapping station will be established in the port Fagerstrand. The optimal solution for Baronessen would be a swapping station in the port of Drøbak. For Tidevind, a swapping station in Filtvedt will lead to the least-cost solution. Baronessen is the cheapest alternative in both scenarios, as it needs the least amount of battery modules. The solution for Tidevind is the only solution where a battery swapping station is established in a small-sized port.

For the fixed battery scenario, all vessels will charge their battery in the port of Drøbak both back and forth. The difference in cost for the vessels are then limited to the size of the battery, where Baronessen with the smallest battery comes out as the winner.

7.4 Route B11

From the timetable presented in Figure 7.6, service B11 is identified to be a commuter service. The timetable presented in Figure 7.7 also shows that the service is set up as a pendulum service with only two stops, doing 13 crossings in the morning and then again in the afternoon. The service starts at Nesoddtangen and ends at Lysaker. Aker Brygge will however be set as both the start and end stop, as this is where the high speed passenger vessels are located when not in use. Stop 0 and 15 represent Aker Brygge, the odd numbers between 1 and 15 represent the port of Nesoddtangen and the even numbers between 2 and 14 represent the port of Lysaker. This setup is in line with the AIS data presented in Figure 7.7. The distance matrix used to solve the problem for route B11 is presented in appendix A.3. The costs for establishing battery swapping stations are 1.5 million NOK in all ports.

Mandag - fredag *Monday - Friday*

	Nesoddtangen	Lysakerbrygge
Første *first*	0630	0638
	0700	0708
	0720	0728
	0740	0748
	0800	0808
	0820	0828
	0840	0848
	1520	1528
	1540	1548
	1600	1608
	1620	1628
	1640	1648
Siste *last*	1700	1708

Mandag - fredag *Monday - Friday*

	Lysakerbrygge	Nesoddtangen
Første *first*	0649	0657
	0709	0717
	0729	0737
	0749	0757
	0809	0817
	0829	0837
	1509	1517
	1529	1537
	1549	1557
	1609	1617
	1629	1637
	1649	1657
Siste *last*	1719	1727

Figure 7.6: Timetable for route B11 (ruter.no, 2022a).

7.4.1 Results B11

As the route is serviced twice a day with a long period of inactivity in between, the results presented in Table 7.11 and Table 7.13 are the optimal solution for the investigation of the first of the two daily sessions.

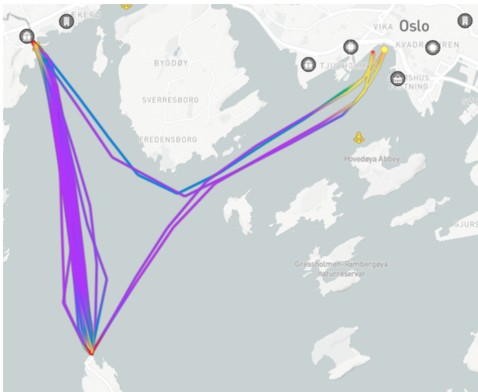

Figure 7.7: AIS-data over 24 hours for route B11 (marinetraffic.com).

400 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	1	2	1
1	-	-	2
2	1	-	-
4	1	-	-
6	1	2	-
7	-	-	2
8	3	-	-
12	-	1	-
13	-	-	1
Objective value [MNOK/year]	4.85	4.35	4.6

Table 7.11: Results showing optimal solution for B11 with 400kWh available per module.

500 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	3	4	1
3	-	-	1
5	-	-	3
9	2	-	-
Objective value [MNOK/year]	4.4	2.65	4.35

Table 7.12: Results showing optimal solution for B11 with 500kWh available per module.

With 400kWh available, all vessels need a battery swapping station in addition to the one in the start node at Aker Brygge. As expected, the cost decreases with

Fixed Battery	x = vessel stops to charge		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	x	x	x
1	x	x	x
3	x	x	x
5	x	x	x
7	x	x	x
9	x	x	x
11	x	x	x
Objective value [MNOK/year]	3.18	3.12	3.15
Battery capacity [kWh]	398	268	325

Table 7.13: Results showing optimal solution for B11 with fixed battery.

increased battery capacity, as presented in the scenario with 500kWh available. The most significant decrease in cost is for Baronessen, which now only needs the swapping station in the starting node.

At first glance, it might be assumed that it would be cheaper to swap out one battery several times at Nesoddtangen for Tidevind with 500kWh/module, where a swapping station is established anyway, instead of taking on three battery modules at once. However, this is not the case, as one round trip from Nesoddtangen back to Nesoddtangen is 5.2 NM. One battery module can power Tidevind for ten nautical miles. This is just short of two roundtrips. The three battery modules taken on at stop five would then have to be replaced by four individual battery swaps for each of the remaining roudtrips before going to Aker Brygge.

For the fixed battery scenario, the optimal solution is again for all vessels to recharge their battery in the same port. As the charging station already is established in the port of Nesoddtangen, the batteries of the vessels are minimized to be recharged every time this port is visited, and thus have quite small batteries.

7.5 Route B22

B22 is serviced only on the weekends and only in the summer season. Similar to B21, this is a pendulum service, but on the west side of the fjord. The distance matrix describing the distances between the stops for route B22 is presented in appendix A.4. The cost of establishing battery swapping stations is set to 1.5 million NOK at Aker Brygge, Fornebu, and in Drøbak. For Vollen, Håøya and

Oscarsborg the cost is set to 1.9 million NOK. The cost in Slemmestad is set to 1.7 million NOK. The results in Table 7.14, Table 7.15 and Table 7.16 presents the optimal solution for one roundtrip from Aker Brygge back to Aker Brygge, where the indexation for the stops starts at 0 at Aker Brygge, following the timetable to the left in Figure 7.8 to stop 6 in Drøbak, before indexing back to Aker Brygge following the setup presented in Figure 6.3.

Lørdag *Saturday*

Aker brygge	Fornebu	Vollen	Slemmestad	Håøya	Oscarsborg	Drøbak
1005	1019	1040	1048	1104	1114o	1124
1305	1319	1340	1348	1404	1414o	1424
1635	1649	1710	1718	1734	1744o	1754

Lørdag *Saturday*

Drøbak	Oscarsborg	Håøya	Slemmestad	Vollen	Fornebu	Aker brygge
1128o	1133o	1143	1159	1207	1228	1240
1428o	1433o	1443	1459	1507	1528	1540
1758o	1803o	1813	1829	1837	1858	1910

Figure 7.8: Timetable for route B22 (ruter.no, 2022a).

7.5.1 Results B22

400 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	4	3	3
6	4	3	3
Objective value [MNOK/year]	5.3	4.7	4.7

Table 7.14: Results showing optimal solution for B22 with 400kWh available per module.

500 kWh/module	Number of modules supplied at each stop		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	3	4	3
6	3	-	3
Objective value [MNOK/year]	4.7	2.65	4.7

Table 7.15: Results showing optimal solution for B22 with 500kWh available per module.

Stop 6, where all vessels swap battery modules in the optimal solution with 400kWh available per module, corresponds to the port of Drøbak, which is halfway on the route. Increasing the capacity to 500 kWh/module reduces the yearly cost for both Baronen and Baronessen, but not for Tidevind. Baronen needs one less module per swap, and Baronessen can now make the whole trip on four battery modules, thus avoiding the cost of establishing an extra battery swapping station. For the fixed battery scenario, establishing a charging station in the port of Drøbak is the

Fixed Battery	x = vessel stops to charge		
Stop	**Baronen**	**Baronessen**	**Tidevind**
0	x	x	x
6	x	x	x
Objective value [MNOK/year]	3.79	3.55	3.65
Battery capacity [kWh]	1768	1225	1442

Table 7.16: Results showing optimal solution for B22 with fixed battery.

optimal solution for all vessels.

7.6 Discussion of Results

Investigating the results as a whole, the importance of a energy-efficient vessel is revealed. Baronessen, which is 18% more energy-efficient than Tidevind, and 44% more efficient than Baronen when it comes to energy consumption at service speed, is the single cheapest option, or one of two equal cheapest options on all of the investigated routes. As expected, the same pattern of the importance of energy efficiency is also observed investigating the same vessel on the same route with different capacities for the battery modules.

Comparing the fixed battery option with the two battery swapping options, using a fixed battery is substantially cheaper on all routes. Due to the way the costs are defined, this was expected, as in the fixed battery option, only one battery is paid for, while for the swapping options, more battery modules are paid for.

Looking into where the optimal placement of the battery swapping stations are located, for each of the routes, there are variations from vessel to vessel on most of the routes. Designing new vessels, this calls for either producing three equal vessels or to choose a solution for one or more of the vessels that are not optimal. As several of the routes use some of the same ports, it should also be considered to place the swapping stations in the joint ports as the total cost might be less even though the placement for each of the routes is not the optimal solution. The optimal location of the swapping stations also vary substantially between the cases with different sizes of the battery modules. What type of battery technology to design for, and the expected development in battery technology should be considered of before doing major investments.

Made as a quite specific decision support tool, the model, and thus the case is limited to looking at the costs coming from the battery swapping system, with stations and battery modules, only. It is important to highlight that the results must be assessed carefully. Even though the costs from the battery swapping system are the same for a route for two different vessels, other things like building expenses, passenger capacity, and hull shape and size will affect the total cost of the vessels. The results from the model should thus be evaluated in a broader perspective together with other expenses.

Chapter 8

Discussion

The main objective of this thesis being to construct an optimization model for decision support, this chapter will provide a discussion of the main trends related to the case study as well as the value of the developed optimization model for battery swapping.

Investigating the results from the case study in chapter 7, an observation is that the energy demand of the vessels plays a prominent role in the economy of a battery swapping system. Especially for a system like this where the capacity of the battery modules, and thus the number of modules needed, affects the objective value largely. As no such battery system has been established before, the costs used for this case seem reasonable as the provider of the battery modules needs a steady income. The companies mentioned in the literature review in chapter 3, launching different battery swapping systems, all points to the economy of scale as an important factor in the viability of their systems. The importance of this can be illustrated by looking at the case above. Establishing a battery swapping system with only one vessel using the system requires a lot of battery capacity for that one vessel. However, by allowing several vessels of different types to use the system, the total number of battery modules needed spread over the number of vessels will be substantially lower.

An example of a system that could use the same battery swapping system as the high speed passenger vessels is a system with container feeder vessels. It has over some years been discussed to move the container port of Oslo further out of the city. Moving it further out of the city and using feeder vessels on the last leg to the city center, using a battery swapping system could be a solution. Having joint swapping stations for the feeder vessels and the high speed passenger vessels would save expenses for both parties. As more and more vessels and services can use modular batteries, the cheaper it becomes for each participant. A system where the modules could be used across transportation industries can also be imagined, serving long haul trucks, for example.

The results from the case study highlights the importance of energy-efficiency, and as presented in chapter 3, there are vessel concepts being developed today focusing on energy efficiency and zero emission high speed passenger vessel solutions, which will allow for a greater range with the same battery capacity. One of the consortia mention battery swapping as a viable option for their concept. Doing some alternations to the other concept designs, one might also assume that more of the concept vessels will be able to use modular batteries. Together with the already launched vessels, Rygerelektra and Medstraum, these projects indicate willingness to invest in this type of technology, and the development of zero emission solutions for this vessel segment. Depending on which estimate of the development of battery technology that becomes reality, many of the services that today are appropriate alternatives for battery swapping might be able to be serviced by high speed passenger vessels with a fixed battery system. Then again, this may lead to longer routes being possible to accommodate by high speed passenger vessels with a battery swapping system.

Comparing the battery swapping cases with the fixed battery case should be done with care, as the energy replenishment is very different. Where the battery swapping is assumed to be performed quickly and without having to alter the schedule of today, this is not possible for the fixed battery vessel. Using a fixed battery vessel will thus also be a question of designing the schedule as well. A possibility to easier be able to compare fixed battery vessels with battery module propelled vessels is to take time into account and assign a cost to the time needed for charging at each stop. This would however complicate the process as the DOD of the battery would have to be monitored throughout the voyage to be able to decide how much time it would need to charge up the battery enough to reach the next charging station.

When it comes to the models themselves, they are limited by a set of assumptions that should be kept in mind utilizing the models. These assumptions include assumptions regarding the input data for the case study, assumptions about the operating context of the vessels, and assumptions of linearity to simplify the models.

The weight of the battery modules was calculated based on the specific weight of an existing battery system provided as a fixed battery. Extra protection and safety measures, which are needed as the modules will be moved around, might increase the weight of the modules compared to this battery system. It is assumed that the vessels are able to have 80% of the vessel's DWT as battery. This is used to establish the maximum number of battery modules or maximum size of the battery a vessel can take. as a first assumption this is okay, but it should be further investigated throughout the design process. Other things than weight might be constricting the number of modules a vessel can take on. Some of the important aspects to consider are the placement of the modules, the area and volume needed, the stability of the vessel and the accessibility to swap the modules.

The battery swapping model developed is quite general and could be used for other similar types of problems. Instead of a battery swapping system, one could look at a vessel propelled by hydrogen, with the possibility of swapping hydrogen tanks in container sizes. This could, for example, be investigated for the Norwegian coastal route, which has a predetermined schedule with 34 stops on a pendulum service making a round trip from Bergen back to Bergen. The model for the fixed option could also be applied to a problem like this as hydrogen has a shorter refueling time than batteries, and the coastal route spends more time in port than a high speed passenger vessel. Refueling time will hence be less important than for a high speed passenger vessel. The size of the tanks would then be dimensioned by the largest distance between two refueling points. As for the battery models, the data input to the model will be important also here. The maximum capacity of hydrogen that is possible to store on board, and the relation between hydrogen consumption and the sailing distance also needs to be established.

Another possible scenario could be a container vessel in liner shipping service with an onboard carbon capture system, where it is to be decided where the CO_2 is to unloaded. The CO_2 could be stored in tank containers. The setup of the model would be the same, but instead of finding the number of battery modules needed to reach the next station, the number of tanks capable of storing the CO_2 emitted to reach the following drop-off point is to be established. In such a scenario, an interesting thing to investigate would be to look at the lost opportunity cost of carrying tanks for carbon capture instead of regular cargo. A possibility would also be to set a cost on the CO_2 emitted straight to the atmosphere and investigate at which cost it would be profitable to do onboard carbon capture, or even a mix, where carbon is captured on parts of the voyage.

The battery swapping model does have similarities with the shortest path problem and the minimum cost flow problem presented in section 5.2. As with the shortest path problem, distance between the nodes is important. For the battery swapping model, the distance is part of the restrictions but is not a part of the objective function as in the shortest path formulation. In similarity with the minimum cost flow problem, the cost is minimized. In the battery swapping model, it is however the cost connected to the nodes that are minimized, and not the flow.

The electric vehicle segment is much more developed than the electric vessel segment. In general, there are also substantially more vehicles than vessels around the world. In contrast to the models presented in section 4.5 which deals with the optimal allocation of charging stations in large road networks with a large number of vehicles, the battery swapping model is developed for a smaller scale, focusing on a predetermined route. As the development for the maritime domain lags behind and is on a smaller scale in general, this is a sensible starting point. The battery swapping model do have similarities with some of the studies describes in Danese et al. (2022) in that it is constructed as a linear optimization problem minimizing the objective function based on costs related to establishing the charging and battery swapping stations.

As presented in chapter 3 there are battery swapping systems being developed for high speed passenger vessels. This shows that there is both will and initiative to develop such solutions. The presented battery swapping model can be a valuable tool in designing such a system, contributing both to important decisions on the vessels and on the allocation of the swapping stations. As suggested in the case, the presented model can be a tool in an iterative design process. However, most ship designs today are developed using a multi-objective multi-disciplinary optimization approach, as described in the literature review. Acquiring more knowledge about battery swapping systems and the system's interaction with other systems onboard a vessel, the model can also be integrated to be a part of a holistic design approach.

In reality, the phasing in of new technology such as a battery swapping system is very expensive and would probably be done step-wise, starting with one battery swapping station. The model can allow for already established stations by fixing the variable deciding if a swapping station is established in a stop on the service through an additional constraint, and setting the establishing cost to zero in that stop when applying the model to expand the battery swapping network. This allows for a more realistic scenario, where one station is first established and tested before it is decided to expand the swapping station network.

Chapter 9

Conclusion

This thesis presents an optimization model for decision support in the design and allocation of battery swapping stations for high speed passenger vessel services. The problem has similarities with other allocation problems, but this specific problem has not been investigated in existing literature. The optimization model was formulated as a BIP problem, and an alternative model for a fixed battery case formulated as a MILP was also presented.

Input to the model for the evaluated case are based on assumptions derived from existing vessels and routes. Compared with already built battery electric vessels, the vessel-related assumptions seem reasonable. However, the cost assumptions are of lower quality and hard to validate. Especially the cost of building and establishing battery swapping stations will vary largely from port to port based on a range of factors. Due to this, the numerical results are of low value. Nevertheless, The case study shows that the model works as intended and is applicable for high speed passenger vessel services of different types of network design for their routes.

The importance of energy-efficiency is emphasized in the literature and confirmed through the case-study. The development of battery technology together with the development of energy-efficient high speed passenger vessel concepts can prepare the ground for a Norwegian fleet of zero emission high speed passenger vessels.

Bibliography

Abioye, O.F., Dulebenets, M.A., Pasha, J., Kavoosi, M., 2019. A vessel schedule recovery problem at the liner shipping route with emission control areas. Energies 12. URL: https://www.mdpi.com/1996-1073/12/12/2380.

Almaas, H.E., 2021. Økning i antall ladestasjoner for ferjer og anlegg for landstrøm. https://www.ssb.no/transport-og-reiseliv/sjotransport\protect\@normalcr\relax/artikler/okning-i-antall-ladestasjoner-for-ferjer-\protect\@normalcr\relaxog-anlegg-for-landstrom.

Andrews, D., Erikstad, S., 2015. State of the art report on design methodology, pp. 90–105.

Baird, A., 2020. Vessel review — rygerelektra – new norwegian ferry breaks all-electric distance and speed records - baird maritime. https://www.bairdmaritime.com/work-boat-world/passenger-vessel-world/ferries/rygerelektra-new-\protect\@normalcr\relaxnorwegian-ferry-breaks-all\protect\@normalcr\relax-electric-distance-and\protect\@normalcr\relax-speed-records/. (Accessed on 05/25/2022).

Berry, R., . Europe: Zes to receive €50 million investment for inland shipping from dutch government - bunkerspot - independent intelligence for the global bunker industry. https://www.bunkerspot.com/europe/56004-europe-zes-to-receive-50-million-investment\protect\@normalcr\relax-for-inland-shipping-from\

protect\@normalcr\relax-dutch-government. (Accessed on 05/02/2022).

Brødrene Aa., 2019. Aero - the future of fast ferries. https://www.braa.no/news/aero-design-revealed. (Accessed on 05/23/2022).

Bukholm, B., Jordbakke, A., Salte, M.L., 2017. Transportutredning hurum royken og søndre asker. https://www.asker.kommune.no/globalassets/samfunnsutvikling/samferdsel/transportutredning_hurum_royken_sondre_asker.pdf. (Accessed on 02/22/2022).

Chen, A., Sen, P.K., 2016. Advancement in battery technology: A state-of-the-art review, in: 2016 IEEE Industry Applications Society Annual Meeting, pp. 1–10. doi:10.1109/IAS.2016.7731812.

Christiansen, M., Fagerholt, K., Nygreen, B., Ronen, D., 2007. Chapter 4 maritime transportation, in: Barnhart, C., Laporte, G. (Eds.), Transportation. Elsevier. volume 14 of *Handbooks in Operations Research and Management Science*, pp. 189–284. URL: https://www.sciencedirect.com/science/article/pii/S0927050706140049.

Christiansen, M., Fagerholt, K., Nygreen, B., Ronen, D., 2013. Ship routing and scheduling in the new millennium. European Journal of Operational Research 228, 467–483. URL: https://www.sciencedirect.com/science/article/pii/S0377221712009125.

Christiansen, M., Hellsten, E., Pisinger, D., Sacramento, D., Vilhelmsen, C., 2020. Liner shipping network design. European Journal of Operational Research 286, 1–20. URL: https://www.sciencedirect.com/science/article/pii/S0377221719308148.

Danese, A., Torsæter, B.N., Sumper, A., Garau, M., 2022. Planning of high-power charging stations for electric vehicles: A review. Applied Sciences 12, 3214. doi:10.3390/app12073214.

Dantzig, G.B., 1990. Origins of the simplex method, in: A history of scientific computing, pp. 141–151.

Dsoke, S., Fuchs, B., Gucciardi, E., Wohlfahrt-Mehrens, M., 2015. The importance of the electrode mass ratio in a li-ion capacitor based on activated carbon and li4ti5o12. Journal of Power Sources 282, 385–393. URL: https://www.sciencedirect.com/science/article/pii/S0378775315003134.

E24.no, 2022. Første batteridrevne hurtigbåt i verden – e24. https://e24.no/det-groenne-skiftet/i/jaeWrz/foerste-batteridrevne-hurtigbaat-i-verden. (Accessed on 05/24/2022).

Ecker, M., Nieto, N., Käbitz, S., Schmalstieg, J., Blanke, H., Warnecke, A., Sauer, D.U., 2014. Calendar and cycle life study of li(nimnco)o2-based 18650 lithium-ion batteries. Journal of Power Sources 248, 839–851. URL: https://www.sciencedirect.com/science/article/pii/S0378775313016510.

Ehmke, J.F., Campbell, A.M., Thomas, B.W., 2016. Data-driven approaches for emissions-minimized paths in urban areas. Computers Operations Research 67, 34–47. URL: https://www.sciencedirect.com/science/article/pii/S0305054815002117.

electrive.com, 2022. Fleetzero develops battery-swapping for ships - electrive.com. https://www.electrive.com/2022/03/17/fleetzero-develops-battery-swapping-for-ships/. (Accessed on 05/02/2022).

ESNA, . esna—informasjonsrapport-fase1.pdf. https://www.trondelagfylke.no/contentassets/26e68ba3c07848c0a79df1a43fb29261/esna---informasjonsrapport-fase1.pdf.

fleetzero.com, . Fleetzero. https://www.fleetzero.com/. (Accessed on 05/02/2022).

Foss, B., 1989. Hurtigbåten, Gammeldampens arvtager. Nordvest Forlag AS.

Fredriksson, H., Dahl, M., Holmgren, J., 2019. Optimal placement of charging stations for electric vehicles in large-scale transportation networks. Procedia Computer Science 160, 77–84. URL: https://www.sciencedirect.com/science/article/pii/S1877050919316618. the 10th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2019) / The 9th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2019) / Affiliated Workshops.

Fridstrøm, L., Alfsen, K.H., 2014. Norway´s path to sustainable transport. Institute of Transport Economics.

Goh, K.I., Cusick, M.E., Valle, D., Childs, B., Vidal, M., Barabási, A.L., 2007. The human disease network. Proceedings of the National Academy of Sciences 104, 8685–8690. URL: https://www.pnas.org/doi/abs/10.1073/pnas.0701361104, arXiv:https://www.pnas.org/doi/pdf/10.1073/pnas.0701361104.

Gurobi Optimization, LLC, 2022. Gurobi Optimizer Reference Manual. URL: https://www.gurobi.com.

Hillier, F.S., Lieberman, G.J., 2013. Introduction to Operations Research. Tenth ed., McGraw-Hill, New York, NY, USA.

Hu, T., Kahng, A.B., 2016. Linear and Integer Programming Made Easy. volume 1. Springer.

IMO, 2000. Hsc-2000. https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/. (Accessed on 12/05/2021).

IMO, 2018. ANNEX 11, RESOLUTION MEPC.304(72), (adopted on 13 April 2018), INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS. IMO.

Innovasjon Norge, 2021. Med kurs mot grønne muligheter. https://www.innovasjonnorge.no/no/verktoy/eksport-og-internasjonal-satsing/tall-og-fakta/gronn-skipsfart/med-kurs-mot-gronne-muligheter/. (Accessed on 02/21/2022).

Jain, S., Ahmad, Z., Alam, M.S., Rafat, Y., 2020. Battery swapping technology, in: 2020 5th IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE), pp. 1–4. doi:10.1109/ICRAIE51050.2020.9358366.

Kartini, E., Genardy, C.T., 2020. The future of all solid state battery. IOP Conference Series: Materials Science and Engineering 924, 012038. URL: https://doi.org/10.1088/1757-899x/924/1/012038.

Krioukov, D., Fall, K., Yang, X., 2004. Compact routing on internet-like graphs, in: IEEE INFOCOM 2004, p. 219. doi:10.1109/INFCOM.2004.1354495.

Lawrence, S.A., 1972. International Sea Transport: The Years Ahead. Lexington Books.

Levander, K., 2012. System based ship design .

Lewis, M., 2021. Check out the netherlands' first electric inland ship – and it's got swappable batteries. https://electrek.co/2021/09/06/check-out\protect\@normalcr\relax-the-netherlands-first\protect\@normalcr\relax-electric-inland-ship-and-its-got\protect\@normalcr\relax-swappable-batteries/. (Accessed on 05/02/2022).

LMG Marin, 2022. Zeff 200-el. https://www.trondelagfylke.no/contentassets/26e68ba3c07848c0a79df1a43fb29261/lmg-marin---informasjonsrapport-fase1.pdf. (Accessed on 05/25/2022).

marinetraffic.com, . Marinetraffic: Global ship tracking intelligence — ais marine traffic. https://www.marinetraffic.com/en/. (Accessed on 05/11/2022).

Martins, J., Ning, A., 2021. Engineering Design Optimization. doi:10.1017/9781108980647.

Meng, Q., Wang, S., Andersson, H., Thun, K., 2014. Containership routing and scheduling in liner shipping: overview and future research directions. https://ro.uow.edu.au/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=4479&context=eispapers. (Accessed on 02/24/2022).

nais.kystverket.no, . Nais - barentswatch. https://nais.kystverket.no/. (Accessed on 06/08/2022).

NIO, 2020. Nio — nio batteri som en tjeneste. https://www.nio.com/news/nio-launches-battery-service. (Accessed on 02/05/2022).

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H., 2007. Introduction. Springer London, London. pp. 1–25. URL: https://doi.org/10.1007/978-1-84628-319-2_1.

Papanikolaou, A., 2014. General on Ship Design. Springer Netherlands, Dordrecht. pp. 1–68. URL: https://doi.org/10.1007/978-94-017-8751-2_1.

Papanikolaou, A., 2019. Holistic Ship Design Optimisation. Springer International Publishing, Cham. pp. 9–42. URL: https://doi.org/10.1007/978-3-030-02810-7_2.

Papanikolaou, A.D., 2020. Review of the design and technology challenges of zero-emission, battery-driven fast marine vehicles. Journal of Marine Science and Engineering 8. URL: https://www.mdpi.com/2077-1312/8/11/941.

Phonrattanasak, P., Leeprechanon, N., 2014. Optimal placement of ev fast charging stations considering the impact on electrical distribution and traffic condition, in: 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE), pp. 1–6.

Rachmawati, D., Gustin, L., 2020. Analysis of dijkstra's algorithm and a* algorithm in shortest path problem. Journal of Physics: Conference Series 1566, 012061. URL: https://doi.org/10.1088/1742-6596/1566/1/012061.

Robert Taggart, e., 1980. Ship Design and Construction. volume 1. SNAME Pulbications, New York.

Ronen, D., 2011. The effect of oil price on containership speed and fleet size. Journal of the Operational Research Society 62, 211–216. URL: https://doi.org/10.1057/jors.2009.169.

Ruter, 2020. Hurtigbåt 2024 - kartlegging av muligheter og konsekvenser. https://ruter.no/contentassets/b3453786cc5a4c\protect\@normalcr\relax3498b621eb8c366f98/hurtigbat-2024-ruterno.pdf. (Accessed on 01/24/2022).

ruter.no, 2021. Linjekart for båt i oslofjorden fra 1. november. https://ruter.no/globalassets/rutetabeller/bat/baat-linjekart-01112021.pdf. (Accessed on 05/06/2022).

ruter.no, 2022a. Rutetabell for b11. https://ruter.no/globalassets/rutetabeller/bat/b11-rutetabell-160821.pdf. (Accessed on 05/19/2022).

ruter.no, 2022b. Rutetabeller for båt b20 fra 1. mars. https://ruter.no/globalassets/rutetabeller/bat/baat-b20-rutetabell-01032022.pdf. (Accessed on 05/11/2022).

ruter.no, 2022c. Rutetabeller for båt b21 fra 6. juni. https://ruter.no/globalassets/rutetabeller/bat/baat-b21-rutetabell-06062022-28082022.pdf. (Accessed on 05/09/2022).

seam.no, 2022. Norled partners up with seam for development of innovative battery system - seam. https://seam.no/norled-partners-up-with-seam-for-development-of-innovative\protect\@normalcr\relax-battery-system/. (Accessed on 05/25/2022).

SES-X, 2022. ses-x-informasjonsrapport-fase-1.pdf. https://www.trondelagfylke.no/contentassets/26e68ba3c07848c0a79df1a43fb29261/ses-x-informasjonsrapport-fase-1.pdf. (Accessed on 05/25/2022).

shift-cleanenergy.com/, 2022. Pwrswäp - shift. https://shift-cleanenergy.com/pwr-swap/. (Accessed on 05/02/2022).

Ship-Technology, 2021. Ampere electric-powered ferry - ship technology. https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/. (Accessed on 12/05/2021).

Singer, D., Doerry, N., BUCKLEY, M., 2009. What is set-based design? Naval Engineers Journal 121, 31 – 43. doi:10.1111/j.1559-3584.2009.00226.x.

Sousa, R., Sousa, J.A., Ribeiro, J., Goncalves, L., Correia, J., 2013. All-solid-state batteries: An overview for bio applications. doi:10.1109/ENBENG.2013.6518400.

Sundvor, I., Thorne, R.J., Danebergs, J., Aarskog, F., Weber, C., 2021. Estimating the replacement potential of norwegian high-speed passenger vessels with zero-emission solutions. Transportation Research Part D: Transport and Environment 99, 103019. URL: https://www.sciencedirect.com/science/article/pii/S1361920921003175\.

Tahara, K., Ishikawa, K., Ishigaki, M., 2020. Battery as a service for electric vehicles: Design and optimization of partially swappable and shareable battery system, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), pp. 1–8. doi:10.1109/ITSC45102.2020.9294582.

The Norwegian Government, 2019. The government's action plan for green shipping.

TrAM-project, 2021. Construction kicks off on world's first zero-emission fast ferry - tram. https://tramproject.eu/2021/06/11/construction-kicks-off-\protect\@normalcr\relaxon-worlds-first-zero-emission-fast-ferry/. (Accessed on 10/08/2021).

Transportutvikling AS, 2022. Tilbud til trøndelag fylkeskommune nullutslipps hurtigbåt. https://www.trondelagfylke.no/contentassets/26e68ba3c07848c0a79df1a43fb29261/transportutvikling-informasjonsrapport-fase1.pdf. (Accessed on 05/25/2022).

Trøndelag Fylkeskommune, 2019. Framtidas hurtigbåter gir null utslipp - trøndelag fylkeskommune. https://www.trondelagfylke.no/nyhetsarkiv/framtidas-hurtigbater-gir-null-utslipp/. (Accessed on 11/09/2021).

Trøndelag fylkeskommune, 2021. Dialognotat fremtidens hurtigbåt del ii. https://innovativeanskaffelser.no/wp-content/uploads/2021/03/dialognotat\protect\@normalcr\relax-fremtidens-hurtigbat-del-ii-080321.pdf. (Accessed on 10/08/2021).

tu.no, 2022. Flere har prøvd og feilet, nå satser theion på svovelbatterier - tu.no. https://www.tu.no/artikler/flere-har-provd-og-feilet\protect\@normalcr\relax-na-satser-theion-pa-svovelbatterier/519677. (Accessed on 05/26/2022).

Verma, J., Kumar, D., 2021. Recent developments in energy storage systems for marine environment. Mater. Adv. 2, 6800–6815. URL: http://dx.doi.org/10.1039/D1MA00746G.

Wang, J., McOwan, S., 2000. Fast passenger ferries and their future. Maritime Policy & Management 27, 231–251. URL: https://doi.org/10.1080/030888300411086.

Wu, P., Bucknall, R., 2016. Marine propulsion using battery power, in: Shipping in Changing Climates Conference 2016, pp. 1–10. doi:10.1109/IAS.2016.7731812.

Zero Emission Services, 2021. Zero emission services commences operation - zero emission services. https://zeroemissionservices.nl/en/zero-emission-services-commences-operation/. (Accessed on 05/02/2022).

Zheng, C., Wang, K., Li, L., Huang, H., Liang, C., Gan, Y., He, X., Zhang, W., Zhang, J., 2021. High-performance all-solid-state lithium–sulfur batteries enabled by slurry-coated li6ps5cl/s/c composite electrodes. Frontiers in Energy Research 8. URL: https://www.frontiersin.org/article/10.3389/fenrg.2020.606494.

Appendix A

Distance Matrices

A.1 B20

	Index/Stop	0	1	2	3	4	5	6	7	8	9	10	11
Index/Stop	port	Aker Brygge	Slemmestad	Vollen	Aker Brygge	Aker Brygge	Slemmestad	Vollen	Aker Brygge	Aker Brygge	Slemmestad	Vollen	Aker Brygge
0	Aker Brygge	0	10,6	12,6	21,6	21,6	32,2	34,2	43,2	43,2	53,8	55,8	64,8
1	Slemmestad	10,6	0	2	11	11	21,6	23,6	32,6	32,6	43,2	45,2	54,2
2	Vollen	12,6	2	0	9	9	19,6	21,6	30,6	30,6	41,2	43,2	52,2
3	Aker Brygge	21,6	11	9	0	0	10,6	12,6	21,6	21,6	32,2	34,2	43,2
4	Aker Brygge	21,6	11	9	0	0	10,6	12,6	21,6	21,6	32,2	34,2	43,2
5	Slemmestad	32,2	21,6	19,6	10,6	10,6	0	2	11	11	21,6	23,6	32,6
6	Vollen	34,2	23,6	21,6	12,6	12,6	2	0	9	9	19,6	21,6	30,6
7	Aker Brygge	43,2	32,6	30,6	21,6	21,6	11	9	0	0	10,6	12,6	21,6
8	Aker Brygge	43,2	32,6	30,6	21,6	21,6	11	9	0	0	10,6	12,6	21,6
9	Slemmestad	53,8	43,2	41,2	32,2	32,2	21,6	19,6	10,6	10,6	0	2	11
10	Vollen	55,8	45,2	43,2	34,2	34,2	23,6	21,6	12,6	12,6	2	0	9
11	Aker Brygge	64,8	54,2	52,2	43,2	43,2	32,6	30,6	21,6	21,6	11	9	0

A.2 B21

	Index/Stop	0	1	2	3	4	5	6	7	8
Index/Stop	Port	Aker Brygge	Nesoddtangen	Flaskebekk	Sjøstrand	Ildjernet	Steilene	Ommen	Fjellstrand	Søndre Lanåra
0	Aker Brygge	0	3,5	4,5	5,25	6	8	9	9,75	12,65
1	Nesoddtangen	3,5	0	1	1,75	2,5	4,5	5,5	6,25	9,15
2	Flaskebekk	4,5	1	0	0,75	1,5	3,5	4,5	5,25	8,15
3	Sjøstrand	5,25	1,75	0,75	0	0,75	2,75	3,75	4,5	7,4
4	Ildjernet	6	2,5	1,5	0,75	0	2	3	3,75	6,65
5	Steilene	8	4,5	3,5	2,75	2	0	1	1,75	4,65
6	Ommen	9	5,5	4,5	3,75	3	1	0	0,75	3,65
7	Fjellstrand	9,75	6,25	5,25	4,5	3,75	1,75	0,75	0	2,9
8	Søndre Lanåra	12,65	9,15	8,15	7,4	6,65	4,65	3,65	2,9	0
9	Lågøya	13,85	10,35	9,35	8,6	7,85	5,85	4,85	4,1	1,2
10	Fagerstrand	14,45	10,95	9,95	9,2	8,45	6,45	5,45	4,7	1,8
11	Aspond	14,85	11,35	10,35	9,6	8,85	6,85	5,85	5,1	2,2
12	Håøya	16,85	13,35	12,35	11,6	10,85	8,85	7,85	7,1	4,2
13	Oscarsborg	18,85	15,35	14,35	13,6	12,85	10,85	9,85	9,1	6,2
14	Drøbak	20,55	17,05	16,05	15,3	14,55	12,55	11,55	10,8	7,9
15	Filtvedt	25,95	22,45	21,45	20,7	19,95	17,95	16,95	16,2	13,3
16	Son	30,35	26,85	25,85	25,1	24,35	22,35	21,35	20,6	17,7
17	Filtvedr	34,75	31,25	30,25	29,5	28,75	26,75	25,75	25	22,1
18	Drøbak	40,15	36,65	35,65	34,9	34,15	32,15	31,15	30,4	27,5
19	Oscarsborg	41,85	38,35	37,35	36,6	35,85	33,85	32,85	32,1	29,2
20	Håøya	43,85	40,35	39,35	38,6	37,85	35,85	34,85	34,1	31,2
21	Aspond	45,85	42,35	41,35	40,6	39,85	37,85	36,85	36,1	33,2
22	Fagerstrand	46,25	42,75	41,75	41	40,25	38,25	37,25	36,5	33,6
23	Lågøya	46,85	43,35	42,35	41,6	40,85	38,85	37,85	37,1	34,2
24	Søndre Lanåra	48,05	44,55	43,55	42,8	42,05	40,05	39,05	38,3	35,4
25	Fjellstrand	50,95	47,45	46,45	45,7	44,95	42,95	41,95	41,2	38,3
26	Ommen	51,7	48,2	47,2	46,45	45,7	43,7	42,7	41,95	39,05
27	Steilene	52,7	49,2	48,2	47,45	46,7	44,7	43,7	42,95	40,05
28	Ildjernet	54,7	51,2	50,2	49,45	48,7	46,7	45,7	44,95	42,05
29	Sjøstrand	55,45	51,95	50,95	50,2	49,45	47,45	46,45	45,7	42,8
30	Flaskebekk	56,2	52,7	51,7	50,95	50,2	48,2	47,2	46,45	43,55
31	Nesoddtangen	57,2	53,7	52,7	51,95	51,2	49,2	48,2	47,45	44,55
32	Aker Brygge	60,7	57,2	56,2	55,45	54,7	52,7	51,7	50,95	48,05

	Index/Stop	9	10	11	12	13	14	15	16	17	18	19	20
Index/Stop	Port	Lågøya	Fagerstrand	Aspond	Håøya	Oscarsborg	Drøbak	Filtvedt	Son	Filtvedr	Drøbak	Oscarsborg	Håøya
0	Aker Brygge	13,85	14,45	14,85	16,85	18,85	20,55	25,95	30,35	34,75	40,15	41,85	43,85
1	Nesoddtangen	10,35	10,95	11,35	13,35	15,35	17,05	22,45	26,85	31,25	36,65	38,35	40,35
2	Flaskebekk	9,35	9,95	10,35	12,35	14,35	16,05	21,45	25,85	30,25	35,65	37,35	39,35
3	Sjøstrand	8,6	9,2	9,6	11,6	13,6	15,3	20,7	25,1	29,5	34,9	36,6	38,6
4	Ildjernet	7,85	8,45	8,85	10,85	12,85	14,55	19,95	24,35	28,75	34,15	35,85	37,85
5	Steilene	5,85	6,45	6,85	8,85	10,85	12,55	17,95	22,35	26,75	32,15	33,85	35,85
6	Ommen	4,85	5,45	5,85	7,85	9,85	11,55	16,95	21,35	25,75	31,15	32,85	34,85
7	Fjellstrand	4,1	4,7	5,1	7,1	9,1	10,8	16,2	20,6	25	30,4	32,1	34,1
8	Søndre Lanåra	1,2	1,8	2,2	4,2	6,2	7,9	13,3	17,7	22,1	27,5	29,2	31,2
9	Lågøya	0	0,6	1	3	5	6,7	12,1	16,5	20,9	26,3	28	30
10	Fagerstrand	0,6	0	0,4	2,4	4,4	6,1	11,5	15,9	20,3	25,7	27,4	29,4
11	Aspond	1	0,4	0	2	4	5,7	11,1	15,5	19,9	25,3	27	29
12	Håøya	3	2,4	2	0	2	3,7	9,1	13,5	17,9	23,3	25	27
13	Oscarsborg	5	4,4	4	2	0	1,7	7,1	11,5	15,9	21,3	23	25
14	Drøbak	6,7	6,1	5,7	3,7	1,7	0	5,4	9,8	14,2	19,6	21,3	23,3
15	Filtvedt	12,1	11,5	11,1	9,1	7,1	5,4	0	4,4	8,8	14,2	15,9	17,9
16	Son	16,5	15,9	15,5	13,5	11,5	9,8	4,4	0	4,4	9,8	11,5	13,5
17	Filtvedr	20,9	20,3	19,9	17,9	15,9	14,2	8,8	4,4	0	5,4	7,1	9,1
18	Drøbak	26,3	25,7	25,3	23,3	21,3	19,6	14,2	9,8	5,4	0	1,7	3,7
19	Oscarsborg	28	27,4	27	25	23	21,3	15,9	11,5	7,1	1,7	0	2
20	Håøya	30	29,4	29	27	25	23,3	17,9	13,5	9,1	3,7	2	0
21	Aspond	32	31,4	31	29	27	25,3	19,9	15,5	11,1	5,7	4	2
22	Fagerstrand	32,4	31,8	31,4	29,4	27,4	25,7	20,3	15,9	11,5	6,1	4,4	2,4
23	Lågøya	33	32,4	32	30	28	26,3	20,9	16,5	12,1	6,7	5	3
24	Søndre Lanåra	34,2	33,6	33,2	31,2	29,2	27,5	22,1	17,7	13,3	7,9	6,2	4,2
25	Fjellstrand	37,1	36,5	36,1	34,1	32,1	30,4	25	20,6	16,2	10,8	9,1	7,1
26	Ommen	37,85	37,25	36,85	34,85	32,85	31,15	25,75	21,35	16,95	11,55	9,85	7,85
27	Steilene	38,85	38,25	37,85	35,85	33,85	32,15	26,75	22,35	17,95	12,55	10,85	8,85
28	Ildjernet	40,85	40,25	39,85	37,85	35,85	34,15	28,75	24,35	19,95	14,55	12,85	10,85
29	Sjøstrand	41,6	41	40,6	38,6	36,6	34,9	29,5	25,1	20,7	15,3	13,6	11,6
30	Flaskebekk	42,35	41,75	41,35	39,35	37,35	35,65	30,25	25,85	21,45	16,05	14,35	12,35
31	Nesoddtangen	43,35	42,75	42,35	40,35	38,35	36,65	31,25	26,85	22,45	17,05	15,35	13,35
32	Aker Brygge	46,85	46,25	45,85	43,85	41,85	40,15	34,75	30,35	25,95	20,55	18,85	16,85

	Index/Stop	21	22	23	24	25	26	27	28	29	30	31	32
Index/Stop	Port	Aspond	Fagerstrand	Lågøya	Søndre Lanåra	Fjellstrand	Ommen	Steilene	Ildjernet	Sjøstrand	Flaskebekk	Nesoddtangen	Aker Brygge
0	Aker Brygge	45,85	46,25	46,85	48,05	50,95	51,7	52,7	54,7	55,45	56,2	57,2	60,7
1	Nesoddtangen	42,35	42,75	43,35	44,55	47,45	48,2	49,2	51,2	51,95	52,7	53,7	57,2
2	Flaskebekk	41,35	41,75	42,35	43,55	46,45	47,2	48,2	50,2	50,95	51,7	52,7	56,2
3	Sjøstrand	40,6	41	41,6	42,8	45,7	46,45	47,45	49,45	50,2	50,95	51,95	55,45
4	Ildjernet	39,85	40,25	40,85	42,05	44,95	45,7	46,7	48,7	49,45	50,2	51,2	54,7
5	Steilene	37,85	38,25	38,85	40,05	42,95	43,7	44,7	46,7	47,45	48,2	49,2	52,7
6	Ommen	36,85	37,25	37,85	39,05	41,95	42,7	43,7	45,7	46,45	47,2	48,2	51,7
7	Fjellstrand	36,1	36,5	37,1	38,3	41,2	41,95	42,95	44,95	45,7	46,45	47,45	50,95
8	Søndre Lanåra	33,2	33,6	34,2	35,4	38,3	39,05	40,05	42,05	42,8	43,55	44,55	48,05
9	Lågøya	32	32,4	33	34,2	37,1	37,85	38,85	40,85	41,6	42,35	43,35	46,85
10	Fagerstrand	31,4	31,8	32,4	33,6	36,5	37,25	38,25	40,25	41	41,75	42,75	46,25
11	Aspond	31	31,4	32	33,2	36,1	36,85	37,85	39,85	40,6	41,35	42,35	45,85
12	Håøya	29	29,4	30	31,2	34,1	34,85	35,85	37,85	38,6	39,35	40,35	43,85
13	Oscarsborg	27	27,4	28	29,2	32,1	32,85	33,85	35,85	36,6	37,35	38,35	41,85
14	Drøbak	25,3	25,7	26,3	27,5	30,4	31,15	32,15	34,15	34,9	35,65	36,65	40,15
15	Filtvedt	19,9	20,3	20,9	22,1	25	25,75	26,75	28,75	29,5	30,25	31,25	34,75
16	Son	15,5	15,9	16,5	17,7	20,6	21,35	22,35	24,35	25,1	25,85	26,85	30,35
17	Filtvedr	11,1	11,5	12,1	13,3	16,2	16,95	17,95	19,95	20,7	21,45	22,45	25,95
18	Drøbak	5,7	6,1	6,7	7,9	10,8	11,55	12,55	14,55	15,3	16,05	17,05	20,55
19	Oscarsborg	4	4,4	5	6,2	9,1	9,85	10,85	12,85	13,6	14,35	15,35	18,85
20	Håøya	2	2,4	3	4,2	7,1	7,85	8,85	10,85	11,6	12,35	13,35	16,85
21	Aspond	0	0,4	1	2,2	5,1	5,85	6,85	8,85	9,6	10,35	11,35	14,85
22	Fagerstrand	0,4	0	0,6	1,8	4,7	5,45	6,45	8,45	9,2	9,95	10,95	14,45
23	Lågøya	1	0,6	0	1,2	4,1	4,85	5,85	7,85	8,6	9,35	10,35	13,85
24	Søndre Lanåra	2,2	1,8	1,2	0	2,9	3,65	4,65	6,65	7,4	8,15	9,15	12,65
25	Fjellstrand	5,1	4,7	4,1	2,9	0	0,75	1,75	3,75	4,5	5,25	6,25	9,75
26	Ommen	5,85	5,45	4,85	3,65	0,75	0	1	3	3,75	4,5	5,5	9
27	Steilene	6,85	6,45	5,85	4,65	1,75	1	0	2	2,75	3,5	4,5	8
28	Ildjernet	8,85	8,45	7,85	6,65	3,75	3	2	0	0,75	1,5	2,5	6
29	Sjøstrand	9,6	9,2	8,6	7,4	4,5	3,75	2,75	0,75	0	0,75	1,75	5,25
30	Flaskebekk	10,35	9,95	9,35	8,15	5,25	4,5	3,5	1,5	0,75	0	1	4,5
31	Nesoddtangen	11,35	10,95	10,35	9,15	6,25	5,5	4,5	2,5	1,75	1	0	3,5
32	Aker Brygge	14,85	14,45	13,85	12,65	9,75	9	8	6	5,25	4,5	3,5	0

A.3 B11

	Index/Stop	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Index/Stop	Port	Aker Brygge	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Nesoddtangen	Lysaker	Aker Brygge
0	Aker Brygge	0	3,4	6	8,6	11,2	13,8	16,4	19	21,6	24,2	26,8	29,4	32	34,6	37,2	39,8
1	Nesoddtangen	3,4	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4	26	28,6	31,2	33,8	36,4
2	Lysaker	6	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4	26	28,6	31,2	33,8
3	Nesoddtangen	8,6	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4	26	28,6	31,2
4	Lysaker	11,2	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4	26	28,6
5	Nesoddtangen	13,8	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4	26
6	Lysaker	16,4	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8	23,4
7	Nesoddtangen	19	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2	20,8
8	Lysaker	21,6	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6	18,2
9	Nesoddtangen	24,2	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13	15,6
10	Lysaker	26,8	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4	13
11	Nesoddtangen	29,4	26	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8	10,4
12	Lysaker	32	28,6	26	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2	7,8
13	Nesoddtangen	34,6	31,2	28,6	26	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6	5,2
14	Lysaker	37,2	33,8	31,2	28,6	26	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0	2,6
15	Aker Brygge	39,8	36,4	33,8	31,2	28,6	26	23,4	20,8	18,2	15,6	13	10,4	7,8	5,2	2,6	0

A.4 B22

	Index/Stop	0	1	2	3	4	5	6	7	8	9	10	11	12
Index/Stop	Port	Aker Brygge	Fornebu	Vollen	Slemmestad	Håøya	Oscarsborg	Drøbak	Oscarsborg	Håøya	Slemmestad	Vollen	Fornebu	Aker Brygge
0	Aker Brygge	0	3,5	10,9	13,1	19,7	21,7	23,1	24,5	26,5	33,1	35,3	42,7	46,2
1	Fornebu	3,5	0	7,4	9,6	16,2	18,2	19,6	21	23	29,6	31,8	39,2	42,7
2	Vollen	10,9	7,4	0	2,2	8,8	10,8	12,2	13,6	15,6	22,2	24,4	31,8	35,3
3	Slemmestad	13,1	9,6	2,2	0	6,6	8,6	10	11,4	13,4	20	22,2	29,6	33,1
4	Håøya	19,7	16,2	8,8	6,6	0	2	3,4	4,8	6,8	13,4	15,6	23	26,5
5	Oscarsborg	21,7	18,2	10,8	8,6	2	0	1,4	2,8	4,8	11,4	13,6	21	24,5
6	Drøbak	23,1	19,6	12,2	10	3,4	1,4	0	1,4	3,4	10	12,2	19,6	23,1
7	Oscarsborg	24,5	21	13,6	11,4	4,8	2,8	1,4	0	2	8,6	10,8	18,2	21,7
8	Håøya	26,5	23	15,6	13,4	6,8	4,8	3,4	2	0	6,6	8,8	16,2	19,7
9	Slemmestad	33,1	29,6	22,2	20	13,4	11,4	10	8,6	6,6	0	2,2	9,6	13,1
10	Vollen	35,3	31,8	24,4	22,2	15,6	13,6	12,2	10,8	8,8	2,2	0	7,4	10,9
11	Fornebu	42,7	39,2	31,8	29,6	23	21	19,6	18,2	16,2	9,6	7,4	0	3,5
12	Aker Brygge	46,2	42,7	35,3	33,1	26,5	24,5	23,1	21,7	19,7	13,1	10,9	3,5	0

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Kunnskap for en bedre verden