



The Blue Light Rail

A Ferry Network Design Problem with Pickup and Delivery

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Abstract

Urbanization, global sustainability issues and a growing population raises concerns for transportation and city-logistics. Increasing supply of transportation alone is not sufficient to meet a growth in transportation. In addition, concerns for increasing pollution and congestion set barriers to traffic. Authorities aim for zero-emission logistics in city centers to meet the Paris agreement and thus address climate change to keep global temperatures from rising above 2°C. Although zero-emission vehicles can reduce the sustainability problem, it interferes the overall congestion. The municipality of Bergen has introduced a solution to these issues. Whilst increasing the public transportation offer by utilizing the inner sea, they aim to create a ferry-service for short-distance travelers. Moreover, waterborne public transportation has shown to be an effective way to provide large-scale transportation for an urban area, and has already been implemented in cities worldwide, such as Amsterdam, Copenhagen and Brisbane.

The idea of a "Blue Light Rail" was first introduced in 2017, but due to high uncertainty, the idea has yet not become practice. Throughout this thesis, a representation of a ferry network design with pickup and delivery (FNDPPD) will be introduced to shed light over some of the questions yet to uncover. The approach is used to investigate how a Blue Light Rail can supplement the transportation offer in the city of Bergen by most efficiently fulfil demand. Experimentation under high uncertainty is conducted, and the analysis uncover the potentials and shortcomings for the service. Pre-set routes are generated and demand is distributed using real bus-data. By utilizing a column generation approach, the model aims to search for the combination of routes that minimizes the required ferries, concerning an estimated demand. Whilst the model aims to minimize a set of routes, further analysis can supplement the research by considering factors such as costs, travel time or the conflict of interest between the operators and passengers.

Keywords – FNDP, PDP, Passenger transportation, Electric vessels, City logistics

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1 Introduction

1.1 Motivation

Increased density, "green-strategy" and a "smart-city" are bullet points in the future prospects of Bergen city (Bergen Kommune, 2018). The goal for zero growth in private transportation and a vision of zero emission within the year 2030 raise concerns for new and low-emission public transportation. This creates a growing concern as the population of Bergen is expected to increase rapidly. Prognoses provided by the municipality claim a growth of 4 000 residents each year until 2030 (Bergen Kommune, 2018). These factors have set ground for a «Blue Light Rail» (BLR) - an electric driven, public transportation in the city sea of Bergen.

Technological development have increased the demand for electric driven ferries in the market for short-distance travels. Not only is there less traffic at sea, distances are often shorter compared to the road, and the seaway can be time-saving. European cities, such as Copenhagen and Amsterdam, have already developed electric ferry solutions for passenger transportation. In September 2019, Oslo launched their first electric ferry "Kongen", and wish to increase electric ferry transportation within the years to come (Nilssen et al., 2018). During the autumn of 2017, the city council of Bergen presented the idea of a Blue Light Rail between the city's districts and close municipalities. In addition to low emission and thus, positive externalities, the routes can easily access areas that are generally difficult for existing road transportation.

The BLR has been an ongoing project and theme of discussion since 2017. A range of parties have been involved, such as Skyss; the municipality council of Bergen; MUST; Fjord1 and Nordled. There are various questions still unanswered. Whilst the idea sounds prominent, there is still uncertainty whether the service will be sufficiently attractive, hence the demand high enough, to cover the costs this investment bears with it. Demand is also a factor relying on the possible users, which are the residents, tourists and work force in the city. With a population of approximately 284 000 (Statistisk Sentralbyrå, 2019), Bergen scores relatively low compared to other European cities. However, the tourism-growth in the city has had a rapid increase the last few years. In 2018, the

number of hotel-visits in Bergen passed 2,2 million yearly visitors (Statistisk Sentralbyrå, 2019). This is a factor that can contribute significantly to the demand for all kinds of transportation. Furthermore, prospects for the municipality might increase interests for visitors to explore other parts of Bergen than the city centre. These plans will be further discussed in Chapter 2.

The traffic basis for a BLR raises significant concerns for investors, as it is the factor raising highest uncertainty. This complicates the searching-process in determining optimal route(s) for the transportation. It is interesting to investigate how an electric driven city ferry could operate in different scenarios, regarding both demand and scheduling. The uncertainty due to lack of experience operating this type of transportation mode also raises the need for scenario-analysis and experimenting. Modelling and testing will create value as it provides an overview of the possible solutions and their corresponding consequences, which I will provide during this thesis.

Autonomous vessels, city bikes, electric scooters and UAV-delivery services are among the innovations that will modify the means with which we move around. In addition, the increased environmental concern and digitization is a combination that can result in radical change within the era of transportation. Throughout this thesis I will focus on electric passenger boats in Bergen, and discuss the effect of different routes given an estimated demand. By analysing such a route using transport modelling, I will analyse both the flexibility and robustness of the ferry as well as how the solution can work in practise. Furthermore, discussion on future logistics and implementations of autonomous ferries and other innovations within transportation will be presented to develop an overview of research yet to uncover.

1.2 Research Question

Based on the discussion above, and the need for more thorough analysis on how to deal with the traffic base for a Blue Light Rail in Bergen, I have formulated the following research questions:

1. *"How can the Blue Light Rail most efficiently fulfill the passenger demand between the given depots?"*

2. *"What combination of routes will minimize the required number of ferries for the Blue Light Rail?"*

The questions cover essential parts to be discovered before the service start its operations. It is impossible to know an exact demand in advance. Nevertheless, to make logical assumptions and investigate scenarios with different demand will help to understand how the ferry-service can operate efficiently. Routes need to be constructed such that it is valuable for passengers, e.g. time-saving compared to private cars or other transportation. From an operational viewpoint, providing value for passengers is just part of the mission. Moreover, it is crucial to find a solution that is cost-efficient from an operational perspective, while providing a favourable service for passengers. The issue I will address is therefore to analyse different routes and evaluate which combination of routes that requires the least ferries. Thus, investigating the routes will be a guide to provide an efficient service both from an operational and a passenger perspective. The discussion will aim to find a balance between the two research questions as the service will have to take into account some conflict of interest regarding the passengers and the operators. This will be more thoroughly examined in the analysis- and results section, where I will further highlight concerns and alternative solutions for the BLR.

2 Background

The "Blue light rail" (BLR) has been a topic in the municipality since 2017, without a clear action. There are several reasons for this, such as uncertain costs, low population leading to uncertain demand and general risks of introducing new services. In the following sections, I will cover why there is a need for such a public transportation; the opportunities and suitability for the city's sea line and development; what issues are yet to uncover and what is covered regarding the BLR. Previous literature will then be introduced and reviewed to provide an overview on related problems and how they have been addressed.

2.1 City Development

Increasing supply of transportation alone is not sufficient to meet a growth in transportation demand (Yu, Peng, Wand, Kong, Cui & Yao, 2015). Yu et al. (2015) further states that developing a large-capacity transportation mode, such as public transportation, is an effective way to provide large-scale transportation for an urban area. Today, most public transportation are road-based, such as rails and buses, and the development of public transportation cannot adequately increase the traffic supply and decrease road congestion. Therefore, for coastal and riverside cities, such as Bergen, developing waterborne transportation is a suitable technique to reduce traffic congestion.

The municipality of Bergen has developed a strategy report for the coastal line including plans for urban consolidation (Bergen Kommune, 2019). Their goal is that 50 % of the housing supply in the municipality until 2030 should be located in the city center. There is consequently expressed a need for intensifying transformation and expansion in the area from Hegreneset to the southern part of Slettebakken. Simultaneously, it is important to maintain the different qualities of the city, both for residents and visitors. The strategy report highlights the coastal line and its unused potential, as it offers attractive landscape and accesses valuable areas. Moreover, the possibility for both transformation and expansion could be accomplished by utilizing the coastal line.

The development plans and prospects for the coastal line includes a set of guidelines (Bergen Kommune, 2019). The report aims to: (1) strengthen the link between the city and sea; (2) set frames for good city development and (3) contribute to connection and

quality in the coastal areas within the municipality (Bergen Kommune, 2019). One of the solutions presented is the BLR, which will contribute to fulfill these criteria.

2.2 Sustainability Issues

Traffic congestion is an increasingly dramatic problem worldwide. Queues for people in daily life to reach their working place and perform regular activity can cause delays and stress in addition to all natural consequences. Stress and delays are factors that diminish quality of life, and needs to be prevented in order to keep and enhance the population and quality of the city (Speranza, 2018). To reduce the number of traveling vehicles, the amount of people travelling must decrease, or the number of people transported in the same vehicle should increase.

Furthermore, institutions today are driven by the sustainability problem. Authorities aim for zero-emission logistics in city centers to meet the Paris agreement and thus address climate change to keep global temperatures from rising above 2°C (Taniguchi & Thomson, 2018). This requires an immense decreased carbon footprint. Taniguchi & Thomson (2018) claims that urban mobility accounts for 40 % of all CO₂ emissions of road transport and up to 70 % of other pollutants from transport. It further highlights that today, bigger cities are dealing with congestion, low air quality, noise and hindrance for visitors, caused mainly by the distribution of vehicles. Urbanization is a contributing factor to these issues, which is not expected to reduce. Around 80 % of the total population in Europe will live in urban areas by 2020 according to The European Commission (2014). This implies a challenge regarding transportation and logistics to avoid congestion, pollution and queues. Electric vehicles will not reduce the number of traveling vehicles, need for parking space or congestion problems. This raises the concerns for solutions that goes beyond low-emission vehicles.

The prospects for the city of Bergen focuses on new innovation and a more carbon efficient traffic. In 2017 the municipality developed a "green strategy" including goals to reduce emissions by 30 % from 1991 to 2020, and 100 % by 2030 (Anfinsen, 2017). The strategy determines long-term goals and strategies to develop a compact, urban, future oriented and green city. The main focus is to restrict traffic in the city and increase the use of electric and zero-emission transportation within industries and passenger transporting

(Anfinsen, 2017).

In the climate budget for 2018, the municipality of Bergen claim that they aim to be a front figure within environmental progress, sustainable development and in adjusting to climate changes. Consequently, Bergen aim to be the greenest Norwegian city (Anfinsen, 2017). Moreover, it is crucial to develop transportation that supports the green strategy and further goals for the city, such as fossil free passenger transportation. The light rail from the city center to Flesland airport is one of these solutions, and has been operating since 22. June 2010. The rail is constantly expanding, with its next target to include Fyllingsdalen and thereafter Åsane. This implies a growing demand for public transportation, and considering the green strategy, this transportation should be emission free. The BLR could be a prominent supplement to the transportation offer in Bergen, not only because it could include additional areas in the city, but also as a contributor to increase the flexibility and robustness of the overall public transportation offer. This can in turn create positive synergies, such as population growth and a simultaneously decreasing use of private cars. These consequences can cause ripple effects in terms of demand growth for public transportation. That being said, such prospecting visions are long-term, and still uncertain.

2.3 Traffic Basis

Even though private cars remain the dominant transportation mode for the vast majority of people, the set of mobility options are growing. In addition to public transportation at land, sea and air, alternative transportation within the sharing economy has increased. Uber, BlaBlaCar and Lyft are some company names providing this kind of ride-sharing. Young people tend to use these new options and postpone the purchase of a private car and the acquisition of a driver's licence (Speranza, 2018).

Major trends in people transportation, such as autonomous vehicles, electric vehicles, collaborate consumption and connection vehicles, will change the way we move (Porter, Linse & Barasz, 2015). Furthermore, Speranza (2018) argues that one of the main reasons that leads people to use their own vehicles is the lack of flexibility of mass transit systems. The mentioned mobility systems usually have fixed schedules and itineraries, with high travel time and low frequency as critical issues. Increasing the variety of offered

transportation can contribute to create increased robustness and thus flexibility for the users, which can save time and even shorten distances. Implementing transportation at sea is additionally a solution that can reduce undesired congestion in the traffic.

The BLR is mentioned in the climate budget as a concrete action for a low-emission future. Such a solution would additionally help tie Bergen to the surrounding municipalities and burst new life to the neglected parts of the quays (Byradet, 2018). In contrast to the existing light rail, the BLR connect other parts of the city and it will not interfere with the infrastructure as it requires no physical rail. In addition, the service can easily expand when demand calls for it. Moreover, the occurrence of the light rail has resulted in remarkable growth in housing prices along the rail, making housing-investments along the light rail lucrative. Increasing residents has in turn made positive demand growth for the light rail, implying continuous ripple effects. The same effect cannot be predicted for the BLR because of higher uncertainty. In contrast to the light rail, there will not be a physical rail, which raises some risk. The ferry service can diminish in short time, e.g. as a consequence of too low demand. The ripple effect will thus not be as visual for the BLR, if visual at all, and therefore we cannot expect the same demand growth. However, improved infrastructure and public transportation, will contribute to higher flexibility and can trigger people to move to the city.

In comparison to the existing light rail, the BLR have some benefits. As an actual rail, the light rail has to be physically built and therefore planned over a longer timeline as it effects and interferes with the city infrastructure. At sea, this is not the case, and thus, the BLR can easily expand its operations. As mentioned, the light rail plans to expand to Åsane, with stops in Sandviken among others. However, the BLR can start its operations, and transfer passengers to Sandviken in good time before the light rail, despite its present non-existence.

The BLR is meant to be a supplement to the existing passenger transportation, which makes demand a crucial factor for this project to be successful. Whilst there are roughly 284 000 residents in the municipality of Bergen in 2019 (Statistisk Sentralbyrå, 2019), traffic basis is a critical factor when deciding whether the BLR, or any passenger transportation, is suited - and if so, profitable. After communicating with involved research-parties for the BLR, I have come to understand the issues and concerns they are facing. Gathering

information on the traffic basis has been troublesome, because of the non-existence of previous experience regarding such short-distance ferry service. These parties are groups within MUST (Mobility lab for development of smart transportation solutions), the Bergen council, Skyss and Norled. In addition, I have taken part in seminars with topics related to the BLR and development of the coastal line within the city. The BLR is a lucrative solution as a supplementary transportation in the city, however there are still questions to be answered and thus reasons why operations haven't yet started. Related costs and boat specifications can easily be measured, but the questions are how the route should look like and if there is sufficient need for such a service.

It is difficult to forecast demand without historical data or reference points. Therefore, to conduct the analysis of the BLR, some assumptions and estimates will be made. These are based on different factors, such as where the residents live and work; distribution of traffic and reports conducted by the involved parties of the project. This will be explained more thoroughly in the Chapter 3 3.

2.4 Bergen City Infrastructure

Bergen has a long history as a port town which has been an extensive part of its industry and transportation, including tourism and as a connection point. The port and the central coastal line characterizes the city's culture and identity. A light rail at sea would be an element to strengthen this identity and preserve the culture. Nonetheless, it can connect important area points more efficiently and contribute to the development of new area points.

Ferry transportation is an increasingly important component of public transport, providing mobility for people in large cities with harbours or rivers (Bell, Pan, Teye, Cheung & Perera, 2019). Public transportation at sea already exists in other cities globally, such as Copenhagen, Sydney, London and Amsterdam. Whilst this service creates public transport opportunities in the cities, the systems also offer other benefits such as activating waterfront land for urban revitalisation and creating tourism opportunities. A variety of alternative transportation opens for more flexible and robust every-day travels, which in turn will help decrease traffic and congestion in the city center (Tanko & Burke, 2017).

In a report developed by the council in Bergen - "Strategi for sjøfronten i Bergens sentrale

deler" (Bergen Kommune, 2019), different problems and opportunities related to the utilization of the coastal line is presented and discussed. The report points out that in a development process in the central areas, conflict of interests can occur. The theme of these conflicts are related to port operations, housing and industry constructions and public rooms. The presented strategy aims to lift the city value for both tourists and residents, and preserve the culture and contribute in converting Bergen to a green and car-free city. One main part of the strategy presents a promenade including the coastline from Breiviken to Laksevågneset, which in turn will lower the barriers between land and sea.

The main harbour in Bergen today is located at Nøstet. The surrounding area is used for both traffic and as a freight terminal. This freight terminal is prospected to move to Ågotnes within 2025, however some passenger traffic such as cruises will continue departing from Nøstet as today. By this time the area around Nøstet will transform and become a part of the central area of the city, with residents and urban functionalities. Nøstet is close to the city centre, as well as universities and the research environments, which makes it an attractive area for future development and expansion of the city centre. Further description of these plans goes beyond this thesis, however it is crucial to cover the importance of the area to further understand the function of the BLR within the particular area. General prospects for the city should be covered to highlight the value which the BLR can bring to the city. With increased population and work places at Nøstet, comes higher demand for transportation. This will support scenarios considering optimistic demand for the service.

2.5 Literature Review

In this section, the theoretical framework will be presented, and previous research will be thoroughly discussed. There is limited related research in the era of passenger transportation at sea. I will however focus on what is already investigated, and how it differs, but also relates, to the case of this thesis. This research include other types of transportation, such as bus and train networks, as well as ferry networks.

First, operational research within the era of transportation will be presented as a basis for further analysis. This will help to understand the history of transportation

science. Secondly, general routing problems in passenger transportation will be presented and shortly discussed. Third, the topic is narrowed down to include waterborne transportation, hence ferry transportation, and the differences between general and waterborne transportation will be explained. Fourth, I will introduce the ferry network design problem (FNDP), and cover the pickup and delivery problem (PDP), as a guiding tool for further representation and methodology. Finally, a presentation of the general ferry network will be provided.

2.5.1 Operations Research in Transportation

After the first optimization models were developed, operational research (OR) has substantially contributed in making transportation and logistic problems competitive. OR was invented as a discipline aimed at developing models and techniques to support decision making (Speranza, 2018). It has captured the complexity of problems and the interactions among parts of a system to improve the quality of decision making. As the OR methods has been dependent on data availability and computer power, the increasing availability of computational capacity have made it more powerful.

The public sector have been responsible for most of the public transportation systems and have been designing the infrastructure for the movement of private vehicles. Therefore, the passenger transportation problems have been faced by this sector. In terms of fleets of vehicles, which have needed to be coordinated in terms of routes, schedules and crew, OR has offered great contributions to the optimization of these systems (Speranza, 2018).

2.5.2 Routing problems in Passenger Transportation

Several papers have studied global problems with respect to the classical vehicle routing problems (VRP). These are aimed towards finding the routes of vehicles, given locations, demands of customers, and time windows (Speranza, 2018). Several studies have been done for the bus network and scheduling (Fan & Machemehl, 2006; Guihaire & Hao, 2008; Cipriani, Gori & Petrelli, 2012). Yan, Liu, Meng & Jiang (2013) proposes a robust optimization model to solve the bus transit network design problem (TNDP). Their solution framework, based on a range of previous algorithms and simulations, guided them towards a methodology to design the bus transit network with random travel

times. Others are also mentioned in the article, which solves the TNDP using different approaches, variables, functions and assumptions on demand elasticity (Gallo, Montella & D'Acerno, 2011). Optimization of the bus network design is extensively researched, however for passenger transportation at sea, there lack research. Operational strategy on waterbuses, hence ferries, include constraints that are unique to this type of transportation and therefore requires other aspects than for other on-land or air transportation.

A waterbus can be defined as "a kind of late-model water passenger traffic mode compared with the tradition traffic mode" (Ye, Yang & He, 2007). It has the following characteristic: Road traffic jam cannot affect it; beautiful landscape and high comfortableness; travel speed is limited with boat and natural conditions; the route choice should be obey to the river; accessibility is lower than traditional public transport because of land use around dock; generally, people who take waterbus, should transfer or walk to the destination; It is beneficial to realize the leisure traffic mode and is more accord with human nature.

Yu et al. (2015) mention several factors to consider when operating a waterbus system. The total cost for the operator is of key interest. Additionally, the costs for the passengers, including the travel time, the times of day of the transfers and the fees, are taken to account when they choose a waterbus. They also point at the conflict of interest between the passenger and the operator. In terms of public transportation convenience, and to meet the needs of the passengers, the service frequency should be as high as possible. A high service frequency however, will result in some wasting of resources and rising operating costs, which does not meet the desire of the operator for economic efficiency (Yu et al., 2015). Thus, building a stable waterbus system requires finding the optimal balance of interest between the parties.

2.5.3 Passenger Transportation at Sea

There are limited studies concerning passenger transportation using ferries, due to its narrow range of applications. A study from Takadama, Majima, Watanabe & Katsuhara (2007) however, investigates an urban traffic network composed of light rail trains, subways, and waterbuses using a quantitative analysis method. The study proved that having diverse modes of transportation in an urban network increased potential for finding new services in a transportation sector. Thus, a combination of waterbuses with other

transportation has the potential of increasing business chances. Van Duin, Kortmann & van den Boogaard (2014) uses simulation to study freight waterborne transport in the inner-city of Amsterdam. It shows that the logistics concept has demonstrated the capability to reduce congestion in the inner-city. Additionally, it is able to satisfy the delivery requirements of the shopkeepers without negatively intervening with other waterborne traffic. Other studies have also been made on the coastal city logistics in Amsterdam (Taniguchi & Thomson, 2018). Overall, the existing research on such ferries are mostly fixed on qualitative analysis on the operative strategy. Some route selection have been analysed and the interest for using the sea for transportation purposes is existent. However, complex network designs for ferries as well as operational research related to the theme are limited.

Yu et al. (2015) proposes a two-stage optimization method for planning the lines and operational strategies for waterbuses in the city Zhoushan in China. Their results improves the current strategy for water transportation in the city. The model considers both the interests of the passengers and operators, from a strategic view you could argue that raising benefits for the passengers will lead to long-term gains for the operators. Thus, considering both passengers and the operators, is consistent to make long-term value for the operators. The case for Zhoushan mainly focuses on placement of hub ports and direct lines. Compared to the BLR, it targets other issues to solve for an already existing waterbus with previous experience and historical data.

2.5.4 The Ferry Network Design Problem with Pickup and Delivery

Network design models are extensively used as representations of a variety of planning and operations issues in transportation, telecommunications, logistics, and production-distribution systems (Crainic, 2000). For freight transportation systems, the representation could be used to assist the decision processes concerning the construction or improvement of infrastructure and facilities and the selection of transportation services among others. The network design formulations are defined on graphs containing nodes, connected by links (Crainic, 2000). Generally, links may have various characteristics, such as capacity, length or costs. Furthermore, the objective is to select links, in order to satisfy some

demand for transportation at e.g. the lowest possible system cost computed as total fixed cost of the selected links (Crainic, 2000). For the BLR, nodes are the pickup and delivery-locations which passengers wish to be transported. Links connect the nodes and will be represented as fixed routes in the network.

The application of the network design problem (NDP) of a ferry transportation, was first formulated as a capacity restricted, multi-commodity flow problem where links are represented as integer decision variables and commodity flows as continuous variables by Lai & Lo (2004). They proposed a network flow-based model to optimize ferry fleet size, ferry routing, and service schedules on one group of routes. The model is formulated as a mixed integer linear program (MILP) and solved by a two-phase heuristic algorithm, which they demonstrate on two ferry services in Hong Kong. A set of feasible paths are generated to provide an upper bound for the optimal solution in phase one, whereas in phase two, the set of feasible paths from phase one are combined to search for improvements to the solution. Similar to Yu et al. (2015), the article combines both the passenger's and the operator's performance measures and thereby concerns the conflict of interest between the two parts. The methodology provides interesting views on the ferry network design problem (FNDP) and solves scheduling and passenger loading in an efficient manner. It focuses on modifying and improving already set routes, which reduces concerns such as time continuity and uncertain demand. The analysis is further tested on real-cases with existing routes and real demand data which makes passenger loading an important factor for the model. As the BLR lack certain data, a more general approach will provide more useful discussion and results for that purpose. Moreover, when more data is available, a method similar to Lai & Lo (2004) could be interesting to assimilate, to further reduce passenger waiting times and streamline its service.

The model presented by Lai & Lo (2004) assumes a set demand and provided a solution based on historical data. Hence, An & Lo (2014) addressed demand uncertainty in the FNDP, in addition to considering user equilibrium flows and hard capacity constraints. They formulate the problem as a two-phase stochastic program in which a schedule of different types of services are derived sequentially. Further on, a user equilibrium assignment with capacity constraint is formulated via a linear programming approach considering overflow delays. They developed a gradient solution approach based on service

reliability to solve the formulation.

Recently, Bell et al. (2019) proposed a novel method to address the FNDP. This paper aims to optimize from a passenger perspective and uses entropy maximization and utility maximization to solve the problem. By the use of spanning trees, they design some ferry lines to maximize expected passenger utility and passenger "fairness". The approaches used, focuses on entropy maximization and considers all possible states of the variables of interest and selects the most likely state consistent with available evidence. Likewise to the case for Lai & Lo (2004), this is something to bear in mind for further research, when the ground for the service is set and more data is available.

Another approach constituting the family of routing problems in which goods or passengers need to be transported from different origins to different destinations is the pickup and delivery problem (PDP). The PDP's have been extensively studied in the literature of network logistic problems (Desrosiers et al., 1995; Savelsbergh and Sol, 1995; Desrochers et al., 1988). They can be conceptually described as finding the optimal way of assigning a set of transportation requests to a fleet of vehicles (initially located at several depots), by minimizing a specific purpose objective function, subject to a variety of constraints. The objective function may include components such as operational costs, number of vehicles or customer's level of service (Cortés, Matamala & Contardo, 2010).

Usually, these problems are defined on a graph including origins or destinations for the different commodities to be transported (Battarra, Cordeau & Iori, 2014). There are three main categories of PDP's based on the type of demand and route structure. First, many-to-many (M-M) problems, are when each commodity have multiple origins and destinations. In addition, any location may be the origin or destination of multiple commodities. We find these problems usually in e.g the management of bicycle or car sharing systems. Secondly, in one-to-many-to-one (1-M-1) problems, the presence of some commodities needs to be delivered from a depot to many customers and of other commodities to be collected at the customers and transported back to the depot. Finally, one-to-one (1-1) problems are characterized by each commodity having a single origin and a single destination between which it must be transported. Typical applications of these problems are less-than-truckload transportation and urban courier operations. In the case for passenger transportation, passengers are being picked up at a certain origin

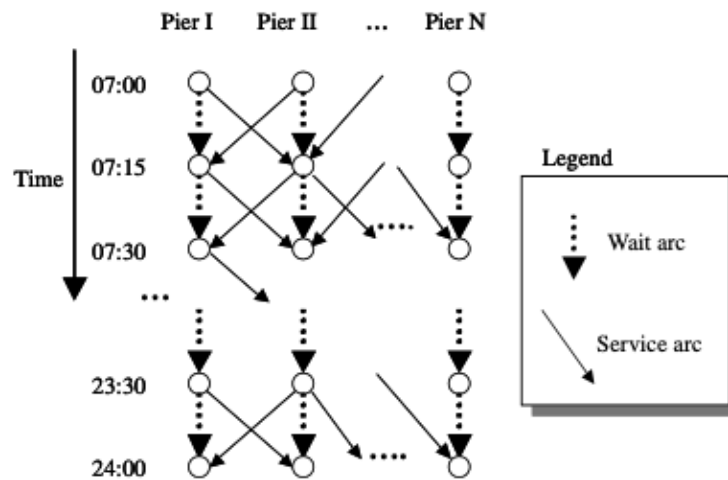
to be delivered to many destinations, or passengers are being picked up at many origins to be delivered to one destination, which can be characterized as a 1-M or a M-1 problem. Work so far on the FNDP has considered equilibrium passenger flows with fixed end ferry stations. This is useful to develop a solution approach to investigate the BLR and how it could operate efficiently within the city of Bergen. Furthermore, the PDP approach can help defining the problem with passengers being allocated to different destinations from different origins.

2.5.5 Representation of a Ferry Network

The ferry network can be characterized for a given demand within a depot-to-depot (or node-to-node) relation. The relation between nodes, called origin-destination (OD) pairs, represent the amount of passengers to be transported from an origin node to a destination node at a specific arrival time. The same procedure follows for a service network design problem (SNDP) which has been used for airline routing and scheduling problems where networks are designed in such a way that passenger demand for travelling from one airport to the other is best satisfied by a given aircraft fleet (Yan & Tseng, 2002; Barnhart, Krishnan, Kim & Ware, 2002).

The NDP presented by Lai & Lo (2004), is an extension of the SNDP, designing a service network for multiple ferry services operating in and around Hong Kong. The network separates the ferry and passenger flow as their main objective aims to find an optimal solution for both. The network is defined by a graph $G(N^f, A^f)$ in which (f) specifies the ferry type. If there is only one ferry type, then only one ferry flow time-space network is needed. (N^f) and (A^f) is the set of nodes and arcs in the time-space network, respectively. The arcs are characterized as both service arcs (S^f) and wait arcs (W^f) which represent a subset of (A^f) . The service arcs are ferry trips, and their corresponding journey time, origins and destinations are specified by some time-space nodes. The schematic presentation of the ferry flow time-space network and is illustrated in figure 2.1 below.

Figure 2.1: The ferry time–space network according to Lai & Lo (2004)



A multi-stop trip is less favorable for passengers as the total travel time is increasing with each intermediate stop. For the operators, a multi-stop can be favorable as it can fulfill demand for a higher number of passengers within shorter time. A FNDP only takes a small time section as a planning interval and tries to match a passenger demand with a given fleet of ferries.

The presented literature provides an overview of what to consider when working on a transportation problem, and how a ferry network can be presented and further analysed. This chapter has presented some of the limited research targeted towards routing and scheduling problems for waterborne passenger transportation. However, in the era of passenger transportation, the studies are numerous. These consider problems such as passenger loading; scheduling lines; minimizing travel time due to capacity constraints and optimizing conflict of interest between passengers and operators. Previous work related to passenger transportation at sea are mainly tested on real cases and aim to improve services already operating, utility for passengers or to reduce operating costs. For the BLR, I will investigate on an even earlier stage with uncertain data. The latter literature can be used as inspiration, although approaches cannot be fully adopted. Due to limited data, I will base the analysis on various demand and schedule specifications. This will be done in order to shed light over the possible outcomes, rather than finding one optimal solution.

3 Data

In this computational experiment, the aim is to examine distribution of a passenger transportation over OD-pairs in the ferry network for the BLR. The network is based in the inner sea area of Bergen and have six provisional depots. Furthermore, the demand is based on workers and residents in the areas around each depot. Due to limited access to data of demand, there will be biases compared to reality. However, by experimenting with both optimistic and pessimistic estimations on demand, the analysis will be based on multiple situations and can therefore provide useful information for further work concerning the service. Furthermore, the passenger distribution is based on real data from a survey conducted on the bus services in Bergen (COWI, 2015).

The aim of this thesis is not to decide which routes fits best for the ferry network, but investigate the functionality of the ferry network and uncover its potential as a supplement to the overall public transportation offer. Furthermore, a model will be created in order to analyse the operation and its outcome in different scenarios. The focus will be put on general interpretations of the result and discussion around solutions made from the model. Data on distances and travel time will be of high importance as these are crucial when discussing costs, operating times, and travel times for passengers. Throughout this chapter, an overview of the required data will be provided, which will set ground for further scenarios.

3.1 Demand Generation

The first data gathered are the passenger demand for each depot, including all passengers going from an origin to a destination at a specific time, hence the OD-pairs in the ferry network. Without historical data, demand will be based on assumptions provided throughout this section. As the aim of this research is to search for solutions that requires the least ferries, the distribution of demand is more important than the number of passengers as such. The data used are estimations formulated in a prospect report for the BLR developed by Onarheim, Bøe, Sundfjord, Sigurdson & Helland (2019) for the municipally in Bergen. The report is conducted as a review, discussing potential routes and technical solutions for the waterborne passenger transportation - the Blue Light Rail.

The report analyses the customer base for 2023 and 2035. Recent trends, new technology and changed behavior towards transportation methods have set base for the analysis.

The results from the report presents various tables containing demand, concerning different assumptions for the years 2023 and 2035. First, three search-criteria was set to quantify the customer base in the areas: (1) residents, employees and students counted within 600 meters (walking distance) from the seaside; (2) residents, employees and students counted within 3000 meters (cycling distance) from the seaside; and (3) residents and employees in the municipally of Bergen with the opportunity to transfer between the bus and ferry service. For each criteria, indexing was used to present the data. Further, assumptions that the new ferry service will result in changing travel behaviour among users have been accounted for. For example, residents from Laksevåg might consider taking jobs at Sandviken when the line between the areas are established. The estimations are set within the time-frame 07:00 to 08:00 for the years 2023 and 2035 and is shown in table A0.1.

Table 3.1: Estimated passenger demand for all OD-pairs from 07:00-08:00 (mon-fri)

OD-pair	Demand for 2023	Demand for 2035
Laksevåg - Nøstet	30-40 passengers	35-50 passengers
Laksevåg - Strandkaien	15-25 passengers	20-30 passengers
Ytre Sandviken - Nøstet	25-30 passengers	45-50 passengers
Ytre Sandviken - Strandkaien	15-20 passengers	45-50 passengers
Indre Sandviken - Nøstet	65-105 passengers	100-120 passengers
Indre Sandviken - Strandkaien	60-90 passengers	85-100 passengers
Laksevåg - Sandviken	10-15 passengers	15-20 passengers
Sandviken - Laksevåg	5-10 passengers	5-15 passengers

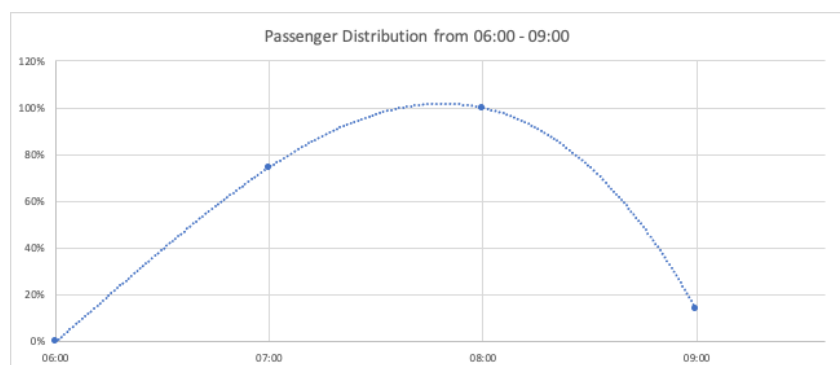
The table suggests a demand within intervals, i.e demand from Laksevåg to Nøstet in 2023 is within the interval [30, 40] passengers. For further analysis, I will refer to the lowest assumed number as the "worst-case" scenario, and lower demand will not be examined. The demand can however, be higher than what is assumed from the criteria. But for the case of simplicity, I will refer to the higher demand in the interval for 2023 as "expected". Moreover, the report provide expanded criteria due to the following assumptions: (1) new technology affects the use of new transportation, for example within micro mobility and electric progress. Consequently, it will be easier for "walkers" to reach the ferry terminals, and hence criteria 1 and 2 can be expanded to > 600 meters and > 3000 meters, respectively; (2) the BLR can be suited to carry cycles, scooters and other micro-mobility

devices; (3) there will be potential to transfer from/to other transportation, and with new technology, this flexibility is expected to increase. Numbers for these criteria is not provided in the report. For further analysis I will however discuss concerns related to increasing demand, as capacity problems may occur in the case of an unexpected demand-boom. In addition, as tourism growth continues, that may also be a contributor to increased demand.

The time frame for the above estimations is restricted to one hour. This is from 07:00-08:00 - when 12,1 % of the daily travels happen. Between 15:00 and 16:00 we find approximately the opposite pattern, this makes sense as this is the time people tend to return from work, whereas 07:00-08:00 is when they tend to arrive (Onarheim et al., 2019). The remaining hours will be calculated patterns found in real data from the bus service in Bergen. The distribution will be presented and explained thoroughly in the Chapter 3 4.

The passenger demand is associated with a distribution within the time horizon. The maximum demand is based on table 3.1, and will be used to distribute the passenger. Due to the uncertain demand, both worst-case and expected demand will be tested for further analysis. The distributions are calculated based on real-data from the bus operation in Bergen, provided in a survey from COWI (2015). Included is only the lines going towards the city center. Therefore, the hours 15:00-16:00 are slightly lower than the hours 07:00-08:00. Some hours during the day are not included in the report, therefore, the distributions are split into morning, noon and evening periods, based on the actual data. In the following, each distribution is presented.

Figure 3.1: Passenger Distribution from 06:00-09:00



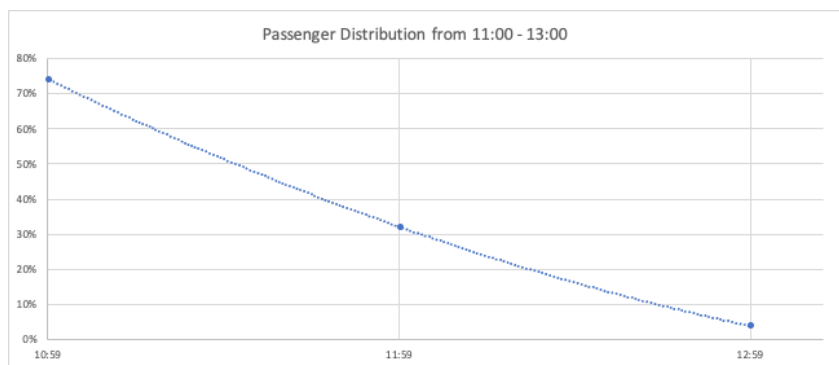
When generating demand for the BLR in the morning period, this distribution will be used. The expected demand provided for the max-hour will therefore be a guide to detect

the demand for the set periods. Corresponding to the demand, is a polynomial, which will be used in further demand-calculations. The polynomial defining the morning distribution is presented in equation 3.1.

$$y_1 = 495,33x^3 - 6348,5x^2 + 21420x - 15295 \quad (3.1)$$

The observed distribution from 11:00-13:00 is provided in figure 3.2 and shows a decreasing trend.

Figure 3.2: Passenger Distribution from 11:00-13:00

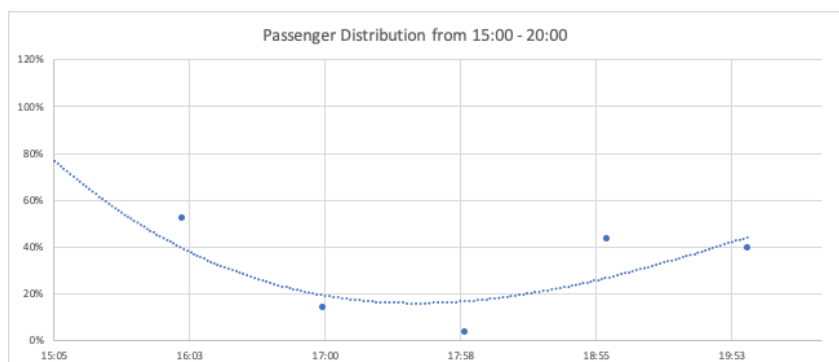


It's corresponding polynomial is provided equation 3.2 below.

$$y_2 = 39,642x^2 - 48,05x + 14,433 \quad (3.2)$$

Finally, the evening distribution, from 15:00-20:00, is presented in figure 3.3. It shows a new peak around 15:00, before the demand decreases and reaches a minimum between 17:00-18:00.

Figure 3.3: Passenger Distribution from 15:00-20:00



The corresponding polynomial is presented in equation 3.3.

$$y_3 = -117,88x^3 + 301,34x^2 - 251,97x + 69,375 \quad (3.3)$$

Utilizing the polynomials will provide a close-to-reality passenger load, however only accounting for the "mainstream" demand. In reality, there will be additional abnormal demand, meaning passengers with requests that differs from the majority, e.g. people working night shifts and thus is on their way home from work during the morning rush with people going to work. Moreover, all demand fulfilled does not mean that all "real" demand will be. Traffic basis is a critical factor for starting operations of the BLR. Thus, it is crucial to target periods where traffic basis is most present. This does not mean that people with abnormal demand cannot use the service, but rather that these passengers are not a priority when creating schedules and routes. For a detailed description of the demand generation process, see Appendix B.

3.1.1 Provisional Depots

The municipality of Bergen has developed a progress plan with suggested depots for public transportation at sea - the BLR. The progress plan is meant to include close-to-sea areas where the transportation at sea can connect with the existing public transportation at land or in a target point in walking distance to the city centre. They suggest the depots to be located in close connection to target points along a planned promenade for the city (Bergen Kommune, 2019). The progress plan further introduces alternative areas to locate the depots, and in new strategic plans they have been narrowed down to the six areas: Indre Sandviken, Ytre Sandviken, Strandkaien, Nøstet, Laksevåg North (Laksevåg N), Laksevåg South (Laksevåg S). In the following part of this section, all areas will be presented and their main characteristics will be shortly introduced, to understand the reasons behind each chosen area.

3.1.1.1 Nøstet

Nøstet is an area in transformation - from port operations to become a city area. Therefore it is identified as a potential with an accessible seafront. The planned horizon for this project is however long and the area will still be limited for the public. Nevertheless, the

area is close to the city center and is therefore considered as a depot for the BLR. The depot should then be placed in immediate contact with urban spaces or a recreation area. Today the area is close to universities and offices, mainly at Marineholmen. Therefore, it is reasonable to assume a high proportion of incoming fleet in the morning, specifically the max-hour between 07:00 and 08:00.

3.1.1.2 Laksevåg

The characteristics of Laksevåg differs from the sea to hinterland. Whilst the sea line is recognized with industry, the hinterland mainly consist of housing. The area is under construction and is considered a substantial part of the city development and reshaping of the sea line. Further plans for the area are still in progress, however focus lie on highlighting the existing qualities of the area and further connect the hinterland to the sea.

3.1.1.3 Sandviken

The surroundings of Sandviken is composed of housing, office buildings, sea-related industry and storage buildings. The area has fragmented contact with the sea and has great potential for further development connecting the sea and city. The area bear a long history and culture. Prospects suggest a range of development in the area, such as a new recreation area at Kristiansholm. In addition, the light rail will pass Sandviken as it expands to Åsane, thus there is reason to assume higher activity and residents in few years.

Big parts of the coastal line is not available because of the city structure and construction, setting a barrier to create a depot. Per now Kristiansholm is suggested as the depot terminal for the BLR, which is also the highlighted landscape element of the area. Other plans are made to develop the area of Kristiansholm to increase its attractiveness.

Sandviken is further described as Sandviken 1(Ytre Sandviken) and Sandviken 2 (Indre Sandviken), where Sandviken 1 is the area around Nyhavn and Hegreneset. Today Hegreneset is a combination of an industry area, detached areas and recreation areas. The prospects from the municipally shows transformations leading to increased housing and block building, implying residential growth. Surveys conducted by the planning and

building services for the municipality, reveals there are 16 464 residents in Nyhavn and Hegreneset. Detailed information of population and area zones can be found in Appendix A. With the prospects made, this number is expected to increase rapidly in the following years. New work-places will additionally account for an increased traffic basis for the BLR.

Hegreneset separates Nyhavn from Breiviken. Access to the sea is primary on the existing quays in both places, but they are not connected. Nyhavn, however, has a close connection to Elsesro, which is a recreation area and will be a focus area during the city development. Both Elsesro and Gamle Bergen are target points in the area, making them important for further development. Strategies also suggest to enhance Nyhavn as a focus point. Recommendations from the progress plan thus suggests a stop at Nyhavn with close connections to existing housing as well as Elsesro og Gamle Bergen.

3.1.1.4 Strandkaien

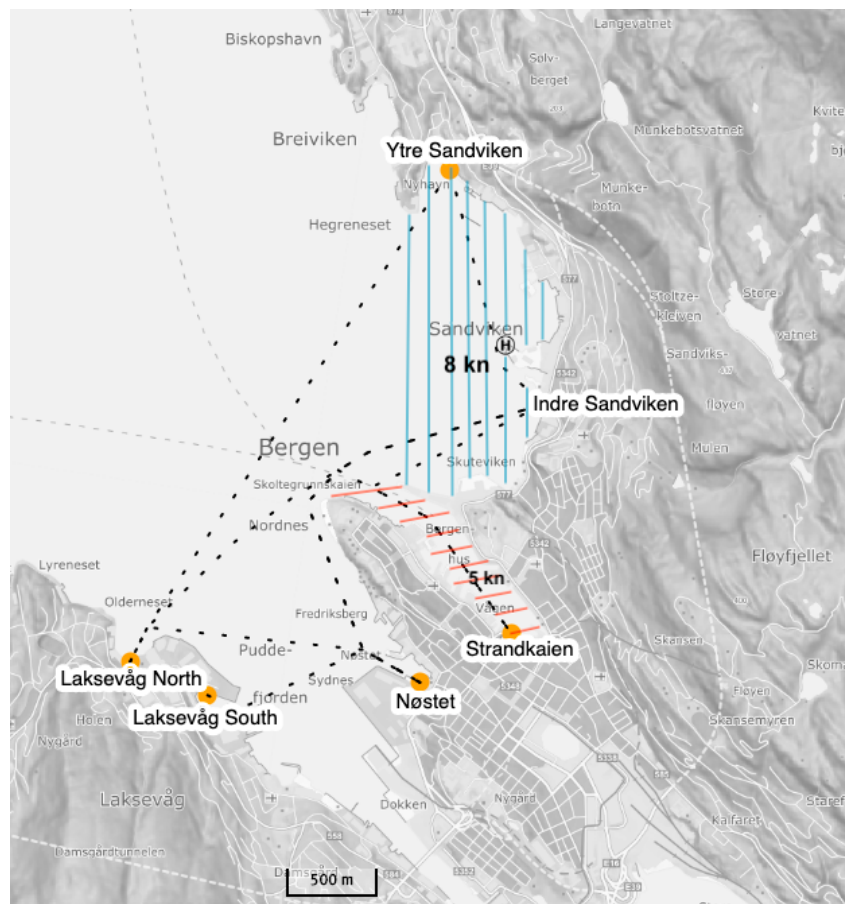
The city center is a connection point as well as it is close to both universities and offices. Strandkaien is an accessible point for a depot, as well as it has high transitional opportunities for passengers traveling further.

With the prospects of a green city, and restricted traffic, it is crucial to supplement the city with new public transportation not interfering with the environment. In addition, tourists visiting Bergen would also benefit from a transportation with easy access to other parts of the city, which in turn can increase the attractiveness of these places.

3.2 Ferry Network

For the ferry network, distances were drawn and calculated using tools from Kartverket. Figure 3.4 visualizes all nodes and the links between them. Since the depots (nodes) are not already established, the real distances may differ from the ones in the figure. They are however created based on areas suitable for depots, and are therefore to be considered valid.

Figure 3.4: Provisional depots and connections



The distances between each node can be calculated to time, although time depends on speed, where some areas are restricted by speed limitations. In figure 3.4, the blue and red lines defines speed restricted areas with speed limit 8 and 5 knots, respectively. The 5 knot area is within Vågen. Kartverket has tools that allows drawing lines to determine nautical distances on their interactive map. The distances could thereafter be used to calculate traveling times. For the distances without speed limitations, 13 knots is used as service speed, likewise to the report from Onarheim et al. (2019). In addition, maneuvering, acceleration and speed reduction should be accounted for. For this purpose, Onarheim et al. (2019) adds two minutes to each route, where the longest routes consist of three steps. For the same purpose, I will add two minutes to each distance between two consecutive nodes. Therefore, a route consisting of three nodes, will include an additional four minutes. In the following tables, table 3.2 and 3.3, the distances and travel times are presented, respectively.

Routes will be made in order to minimize required ferries. Not all ferries will be allocated

	Sandviken1	Sandviken2	Strandkaien	Nøstet	Laksevåg S	Laksevåg N
Sandviken1	-	0.77 nmi	1.61 nmi	1.73 nmi	1.82 nmi	1.73 nmi
Sandviken2	0.77 nmi	-	1.18 nmi	1.42 nmi	1.54 nmi	1.49 nmi
Strandkaien	1.61 nmi	1.18 nmi	-	1.41 nmi	1.53 nmi	1.56 nmi
Nøstet	1.73 nmi	1.42 nmi	1.41 nmi	-	0.70 nmi	0.94 nmi
Laksevåg S	1.82 nmi	1.54 nmi	1.53 nmi	0.70 nmi	-	0.65 nmi
Laksevåg N	1.73 nmi	1.49 nmi	1.56 nmi	0.94 nmi	0.65 nmi	-

Table 3.2: Distances between nodes in the ferry network

	Sandviken1	Sandviken2	Strandkaien	Nøstet	Laksevåg S	Laksevåg N
Sandviken1	-	6,75 min	14,45 min	9,84 min	10,26 min	9,64 min
Sandviken2	6,75 min	-	12,22 min	10,26 min	9,36 min	9,15 min
Strandkaien	14,45 min	12,22 min	-	11,89 min	12,45 min	12,56 min
Nøstet	9,84 min	10,26 min	11,89 min	-	4,22 min	5,34 min
Laksevåg S	10,26 min	9,36 min	12,45 min	4,22 min	-	4,00 min
Laksevåg N	9,64 min	9,15 min	12,56 min	5,34 min	4,00 min	-

Table 3.3: Traveling times between nodes in the ferry network

the same routes, if any. The report from Onarheim et al. (2019) mentions that a direct connection between Laksevåg S and Laksevåg N is unnecessary, as road distance between them are too close. After examining the distances, I have concluded that treating Laksevåg as two depots will not provide enough value to the model due to the following observations: (1) the travel times from Laksevåg N and Laksevåg S to the four other nodes are close to equal; (2) on land, distances between the areas are within walking distance and (3) demand is considered for Laksevåg as one, and therefore it makes sense that the depots are as well. Consequently, I will refer to Laksevåg as one depot and include the calculated numbers from Laksevåg S. This being said, the results may as well apply to Laksevåg N, as the time differences are negligible.

Nøstet and Strandkaien is neither suited for direct transport, as the sailing distance is longer than any other transfer option via land, included walking. In addition, because of the 5 knot speed limit within Vågen, the sailing time between the two nodes is rather high. Including a direct connection between them is consequently destroying value for any route combination. For example, a direct route between Strandkaien and Laksevåg is estimated to have a duration of 12.45 min, whereas if the route sails via Nøstet, the duration nearly doubles.

Furthermore, is neither expedient to establish too short routes, as the ferry will provide low competitiveness to other transportation. Such routes can also be easily solved by cycling, walking or existing public transportation. That being said, a route might include both Sandviken 1 and Sandviken 2 if both origins include passengers going to a particular destination. Moreover, from an operative perspective, including two close nodes might increase total value. Furthermore, connections between Laksevåg and Sandviken are of high passenger value, as they have potential to be significantly time-saving compared to road transport.

As mentioned, a direct connection between Strandkaaien and Nøstet will not exist. In addition, not all direct routes will be considered. Whilst some direct routes are excluded, a connection between the nodes can still be implemented within a route of three or four nodes. For example, whilst Sandviken 1 and Sandviken 2 will not exist as a route, a route including Sandviken 1, Sandviken 2 and Laksevåg can. Due to assumptions made throughout this section, the following direct routes will not be considered:

- Sandviken2 - Sandviken1
- Strandkaaien - Nøstet
- Sandviken1 - Nøstet
- Sandviken2 - Nøstet

Nøstet has no direct route to Sandviken 1 and Sandviken 2, because of the assumption that Nøstet is too close Strandkaaien and it would be unnecessary to have direct routes. For passengers with this demand, a solution is to arrive at Strandkaaien, and either walk or use another transportation to the final destination. There might alternatively, be a route going from Sandviken to Laksevåg via Nøstet.

Based on the discussion above, 20 routes have been established, with no routes combining all five depots. This is due to the restriction that neither route includes both Nøstet and Strandkaaien. This restriction also limits the travel time each passenger must accept. As previously mentioned, An & Lo (2014) claims that multi-stop trips is less favourable for passengers as the total travel time increases with each intermediate stop. With four stops, the maximum number of intermediate stops for a passenger is two. For the operators, a multi-stop can be favourable as it can fulfill demand for a higher number of passengers

within a short time. Table 3.4 below summarizes the routes. Depending on number of ferries, only a few of these routes will be chosen as fitted for the ferry network.

	Node 1	Node 2	Node 3	Node 4
Route 1	Sandviken1	Sandviken2	Strandkaien	
Route 2	Sandviken1	Strandkaien		
Route 3	Sandviken1	Laksevåg		
Route 4	Sandviken1	Sandviken2	Laksevåg	
Route 5	Sandviken2	Strandkaien		
Route 6	Sandviken2	Laksevåg		
Route 7	Nøstet	Sandviken1	Sandviken2	
Route 8	Nøstet	Sandviken1	Laksevåg	
Route 9	Nøstet	Sandviken2	Laksevåg	
Route 10	Nøstet	Laksevåg		
Route 11	Strandkaien	Laksevåg		
Route 12	Laksevåg	Sandviken1	Sandviken2	Strandkaien
Route 13	Laksevåg	Sandviken1	Strandkaien	
Route 14	Laksevåg	Sandviken2	Strandkaien	
Route 15	Laksevåg	Sandviken1	Sandviken2	
Route 16	Sandviken2	Nøstet	Laksevåg	
Route 17	Laksevåg	Nøstet	Sandviken1	Sandviken2
Route 18	Laksevåg	Nøstet	Sandviken2	
Route 19	Laksevåg	Nøstet	Sandviken1	
Route 20	Sandviken1	Nøstet	Laksevåg	

Table 3.4: Selected possible routes in the ferry network

4 Methodology

4.1 Problem Description

The problem is a ferry network design problem with pickup and delivery (FNDPPD), concerning a fleet of ferries that must collect and deliver passengers according to their demanded times and locations. The network can be defined as a graph, $G(N^f, K^f)$, where N is the set of nodes and $K\{k1, k2, \dots, km\}$ is the set of routes. D is then the set of OD-pairs to be transported through the network, denoted as d . An OD-pair is a group of passengers with an equal request, meaning that they have the same demanded time of arrival, origin and destination. The nodes in the network are all both origins and destinations for the passengers. Distances between the nodes, are defined by a travel time t_{ij} from node i to $j \forall (ij) \in N$. To account for additional time due to pickup and delivery, a service time s is added to each node i included in a route k . Each route includes a minimum of two nodes and a maximum of four, as presented in table 3.4. Passengers will be allocated routes that correspond to their request. In addition, some considerations regarding passenger travel times and earliest time of arrival will be taken into account, which will be presented in the next section. Time is crucial for the FNDPPD, both for the passengers, but also for operational reasons, as time is valuable for the services revenues. It is clear that from a passengers perspective, direct routes are the best alternative. From an operational viewpoint, it is preferable to sail at full capacity along short distances, thus multi-trips are generally more efficient. The objective is to minimize the routes needed to fulfill demand, hence to reduce total travel time, as well as investment costs for the ferries. Furthermore, the constraints will ensure demand is fulfilled at a certain level, providing a lucrative service. All passengers are assumed to have the same priority. This makes sense if the fare prices are the same regardless of distance traveled. In addition, as all demand needs to be fulfilled at their request, prioritizing some passengers would not influence the results. At each node, the demand is distributed during three time frames divided throughout the day. I will thus analyse the ferry network during the morning hours from 06:00-09:00, around noon from 11:00-13:00 and during the evening from 15:00-20:00. Due to lack of real data, the following assumptions are made:

- All ferries are assumed to be homogeneous. They will have the same speed and

capacity, as well as operating cost per hour. I will not include costs in the model, as measures of travel time and the number of required ferries points towards similar conclusions. If all ferries are equal, the need for employees and cost of operating are equal for all, and thus time will give a sufficient indication of the expected cost.

- All passenger groups are treated as equally important. Whilst all demand should be fulfilled, the results would not change under the account of "fairness". E.g if one passenger group would have a higher priority than another, they would still both be considered due to the requirement that all demand should be fulfilled. Consequently, the result would not change.
- Capacity is held for all ferries at all times and will thus not be included as a constraint nor limitation to the model. The reason for this is the uncertain capacity and the expected demand. As the expected demand is rather low, and there is still questions if there are enough demand for the service of the BLR, including capacity constraints will not provide significant changes to the result. Due to the complexity of the problem, capacity-questions is therefore limited to the discussion part of the analysis.
- Passengers are assumed to only be allocated to one route, meaning that a transit with changing ferries is not applicable. This makes sense for a city ferry transporting passengers relatively short distances. Moreover, a passenger going Sandviken-Laksevåg would, in the majority of cases, not join route $k1$ from Sandviken to Nøstet and then another route $k2$ from Nøstet to Sandviken. There might be cases where this situation occurs, but this falls beyond the "normal" passenger, and is therefore outside of scope for this analysis.

4.2 Model Formulation

In this section, I will present a formulation of the ferry network design problem with pickup and delivery (FNDPPD) for the Blue light rail. Due to the complexity and uncertainty related to the problem, the approach have been divided into three phases. Uncertainty refers to the lack of real data. The input data will therefore be generated based on assumptions and closely-related data, described in Chapter 3.3. First phase of the approach concerns possible routes, including depots, timetable generation and

frequency. The second phase will focus on the OD-pairs and their requests. Results from phase one and two, will be presented in one table each - a timetable for all routes and a demand-table for all OD-pair. Finally, the third phase will be to minimize the routes needed to fulfill demand, using column generation. Merging the tables from phase one and two into a binary matrix will then be used as a representation of which routes can fulfill the demand for each OD-pair. A linear programming approach will determine the optimal combination of routes. Table 4.1 presents notations which will be used to formulate the model.

Table 4.1: Sets, parameters, and variables used in the FNDPPD

Sets	Description
N	Set of nodes in the network
K	Set of potential routes in the network
W	Set of trips in the network
D	Set of OD-pairs in the network
Parameters	
T_l^{begin}	Time trip l begins $\forall l \in W$
T_l^{end}	Time trip l ends $\forall l \in W$
Q_d	Number of passengers in $D \forall d \in D$
β_d	Patience for passengers
T_d^{dem}	Demanded time of arrival for passenger $d \forall d \in D$
θ	Minimum number of passengers for pickup
t_{ij}	Travel time from node i to j
s	Service time
T_h^{start}, T_h^{stop}	Start and stop of time horizon, respectively
T_{ik}	Time at node i during route $k \forall k \in K$
T_{il}	Time at node i during trip $l \forall l \in W$
$T_{kd}^{delivery}, T_{kd}^{pickup}$	Time passenger d is delivered and picked up by route k , respectively
$v_{i,d}, v_{j,d}$	Pickup- and delivery-location for passenger d , respectively
u_{ik}	nodes within a route $k, \forall i \in N, k \in K$
Variables	
T_d^{ear}	Calculated time of earliest arrival for passengers in OD-pair d
x_k	1 if route k is used, 0 otherwise
α_{dk}	1 if passengers in OD-pair d is assigned to route k , 0 otherwise
z_{ld}	1 if passengers in OD-pair d is assigned to trip l , 0 otherwise

4.2.1 Route Schedule Generation

The first phase will generate the schedules all possible routes in the ferry network, $K \in G$. The routes will have continuous duration from the start to the end of the time horizon, being from T_h^{start} to T_h^{end} . Trips l are additionally included, and are defined as whole numbers $W\{1, 2, \dots, n\}$. A trip is the duration from the first node i to the last node m of K for all times the route repeats itself. With continuous duration, the passengers can be picked up at the last node of the route, and be delivered at the first or second node of the next trip, $(l + 1)$. Each trip l is associated with a time window $[T_l^{begin}, T_l^{end}]$, which is the time from a node i to node m within a route k . Furthermore, service time s should be added to each visited node within a trip l . Hence, the time window is defined as an interval and presented in equation 4.2 below.

$$[(T_{m(l-1)} + s + t_{mi}), \sum (T_{il} + s + t_{ij})] \forall l \in K, (i, j, m) \in N, \quad (4.1)$$

where $T_m(l - 1)$ indicates that a trip will begin when the ferry has traveled back to the first node i from the last node m on the previous trip. The route schedule generation approach utilizes equation (1) to calculate the time windows for the specified time horizon and summarizes them in a timetable. The routes will have continuous duration and thus no breaks are implemented. The calculations in the schedules are based on a start time, such that $T_{l_0}^{begin} = T_k^{start}$, where $T_{l_0}^{begin}$ defines the first departure of $l1$. Three start times will be implemented as constants such that different schedules will be considered in the search for suitable routes. T_k^{start} will be set to 06:00, 06:05 and 06:10, and three time schedules for each route will be generated. Having three different schedules for one route might also uncover need for higher frequency for some routes. Additional start times could also be implemented. However, increasing patience β_d would be another solution to discover effects of modifying schedules. Whilst increased patience increases the chance of finding suitable routes, it can be determined whether the chosen routes would satisfy passengers needs further with a slight movement in the schedule. E.g if a route can deliver 50 passengers to their destination but the majority is delivered 20 minutes before demanded arrival time, then a slight change in the schedule might be beneficial. The output of this phase are timetables for all routes, which will be further utilized in the

column generation phase.

4.2.2 Passenger Requests

A passenger demand table will provide a summary of all OD-pairs D , and the corresponding number of passengers, such that Q_d is the number of passengers per respective origin and destination. $v_{i,d}$ and $v_{j,d}$ represent the origin and destination for a passenger d and must correspond to their assigned routes, such that $v_{i,d}$ and $v_{j,d}$ must both lie within u_{ik} . The time window defining demanded and earliest time of delivery will be given as the interval $[T_d^{dem}, T_d^{ear}]$. T_d^{ear} is a variable depending on the passenger patience, β_d . The interval defining the passengers time window is therefore given as the following equation:

$$[T_d^{dem}, T_d^{dem} - \beta_d] \quad \forall d \in D, \quad (4.2)$$

where $T^{ear} = T^{dem} - \beta_d$. The reason for providing patience in stead of a minimum travel-time per passenger group is that a patience can be given as a constant for all demand, whereas a minimum travel time would differ for all passenger groups. If a passenger is traveling from Sandviken 1 to Strandkaaien, the minimum expected travel time would be significantly less than if the same passenger was going to Laksevåg. This would also be a relative number depending on what the alternatives are, e.g if the passenger's alternative is to drive by car, his expected travel time is less than if he usually takes the bus, or rides his bike. Consequently, using patient for arrival time I make sure the passenger arrives at his designated delivery within acceptable time. The patience can be easily modified during experimentation of the model. Whilst the time window specifies the time concerns for a passenger d , $v_{i,d}, v_{j,d}$ define their requested origin and destination, respectively.

4.2.3 Column Generation

The last phase of the modelling approach is the column generation. This phase aims to find the combination of routes and passengers that minimizes the number of routes k , while fulfilling the demand d . By implementing the output generated in phase one and two, this comprises an intuitive optimization model which can be solved utilizing RStudio's linear programming-function "lpSolve". Appendix D D provides some table

examples from the approach. Whilst multiple routes k can fulfill demand for OD-pair d , a matching-approach will be used in order to create a binary matrix. Rows represent OD-pairs d and columns represent routes k . In the generated matrix, 1 defines whether a route can fulfill demand for a passenger d , and 0 otherwise. The objective function then utilizes this matrix in order to minimize the routes required. The objective function (1) is presented below.

$$\min \sum_{k \in K} x_k \quad (1)$$

where x_k is a binary variable equal to 1 if route k is used, and 0 otherwise. The matrix generated is build under a set of constraints, presented below.

$$\sum_k x_k \alpha_{dk} \geq 1 \quad \forall d \in D \quad (2)$$

$$T_d^{dem} \geq T_{kd}^{delivery} \geq T_d^{ear} \quad \forall d \in D, k \in K \quad (3)$$

$$T_k^{pickup} d \geq T_k^{delivery} d \quad \forall k \in K, d \in D \quad (4)$$

$$z_{ld} \geq z_{(1-l)d} \quad \forall l \subset K, d \in D \quad (5)$$

$$x_k \in \{1, 0\}, \alpha_{dk} \in \{0, 1\}, z_{ld} \in \{0, 1\} \quad (6)$$

Constraint (2) makes sure all OD-pairs d are covered by at least one route, where α_{pk} is a binary variable equal to 1 if passenger p is covered by route k , and 0 otherwise. Each passengers patience β_d is accounted for in constraint (3), saying that the time route k delivers passenger d at the respective destination needs to lay within the earliest and demanded time of arrival for passenger d . Constraint (4) ensures that the time of pickup is before the time of delivery. Passenger d can be picked up and delivered at two consecutively trips l , ensured by constraint (5). (6) states that x_k , α_{dk} and z_{ld} are binary variables.

During analysis some constant parameters, such as β_d , can be modified due to the uncertain data. Concerning pickups for only OD-pairs that include passengers above a certain number is reasonable, as including them could both destroy profits and might also go at the expense of a large passenger group of e.g 20 people. The quantity of passengers in a group is given by Q_d , and θ is a constant defining the required passengers in OD-pair d to be considered for a pickup. The passengers patience, β_d will also be modified to see the effects of the limitations it reveals. Furthermore, modifying the time horizon will be beneficial to see which routes provides value for each period. It is reasonable to believe that the number of required routes are not equal during the period 09:00-10:00 as it is in

the max-hours. The time horizon, denoted h is defined as the interval $[T_h^{start}, T_h^{stop}]$. The additional constraints will be introduced in the following.

$$Q_d \geq \theta \quad \forall d \in D \quad (7)$$

$$T_l^{begin} \geq T_h^{start}, T^{end} \leq T_h^{stop} \quad \forall l \in K \quad (8)$$

Constraint (7) makes sure that the quantity of passengers in a group is higher than the required. To further make sure all time windows are within the time horizon, constraint (8) is introduced.

Minimizing the required routes will reveal the number of ferries required to operate. By also minimizing the amount of trips l for each route, some ferries might even be allocated to multiple routes, thus changing routes during the day, depending on demand. Therefore, an additional objective is introduced, and will be experimented with during analysis.

$$\min \sum_{l \in K} x_l \quad \forall l \in W \quad (9)$$

During analysis, both objectives will be tested, to provide closer insights to the ferry network. There are no constraints making sure the ferries are not at the same location at the same time. The benefit of having such a constraint is to prevent collisions and thus maintain feasible solutions. The reason for not implementing it is that the time schedules set for the routes are not certain, and it is more important to reveal valuable routes in terms of pickup and delivery rather than make complete schedules. In addition, setting such a constraint can be a hinder in the search for useful routes. Moreover, as the quays are not yet settled, there might even be possible to have more than one ferry at a node simultaneously.

5 Analysis

Throughout this section I will present results and analysis from different outputs using the model presented in Chapter 4. I will investigate the scenarios using the routes and respective trips presented by the model, by modifying the constants being the passengers patience β ; T_h^{start} and T_h^{stop} and the minimum required number of passengers for a passenger group to be accounted for. In addition, I will investigate exclusively which trips, $l \in W$, are necessary for the time horizons analysed. Moreover, I will consider both objective functions (1) and (9) which aims to minimize routes and trips, respectively. In the following sections, results and analysis using morning-, noon- and evening distribution will be presented in separate sections.

5.1 Ferry Network Flow - Morning Distribution

The number of passengers are currently set to the expected number for 2023, and distributed using the morning distribution presented in Chapter 3. First, I will test the model with the following parameter values: $\beta_p = 15$ minutes, $\theta = 5$, $T_h^{start} = "06 : 00"$ and $T_h^{stop} = "09 : 00"$. This results in a solution of the seven following routes: k1,k2,k7,k9,k12,k14, and k19, distributed to 555 passengers. With a continuous duration, this means a total of 61 trips within the routes, and thus an average of 9 passengers per trip. Seven routes would require seven ferries, as these have continuous duration throughout the set time horizon. Among the chosen routes are multi-stop routes with both three and four nodes. Route k7 and k12 are routes with four nodes, meaning that some passengers can risk a travel with two additional stops. From a operational perspective, the routes are overall efficient and transfers passengers between all the nodes in the network. The two routes alone fulfill demand for 222 passengers, equivalent to 40 % of the demand in the respective time period. The travel times are neither unreasonable for the majority of the passengers. Although, if passengers would travel from Nøstet to Laksevåg, the shortest travel time to expect is 20 minutes, on a distance usually taking < 5 minutes. In the morning rush however, this distance is rather rare, as passengers are usually going towards the city center. When discovering routes for the "mainstream" demand, such concerns are therefore of low importance.

A minimization of trips, provides a solution of 21 trips and slightly below 8 hours within the respective time horizon. These trips are within a total of nine routes, where five routes correspond to the latter. In addition, some routes require higher frequency. For example route k7 and k14 should have both ferries starting at 06:00 and 06:05. The respective routes have a duration of approx. 27 and 21 minutes, respectively. With the suggested increased frequency, additional ferries are required. Even though looking at the total travel time exclusively highlights the benefits of minimizing trips, it could be extremely costly concerning other factors. Having more than nine ferries operating requires the cost of investing in nine ferries, crew and captain for all ferries, in addition to charging costs and docking. It is however interesting to understand the value of splitting the routes to only operate when the need is present. Furthermore, some trips from different routes can be allocated one ferry if time allows it. This would mean an implication of flexible routes. For example, route k16(16)¹ arrives at Laksevåg 06:26. This can be combined with route k13(13) departing from Laksevåg 07:11 going towards Strandkaaien. In addition, route k9(16) from Nøstet to Laksevåg fits the schedule. These three routes alone would not equal a route going continuously, but is rather a short example of how the minimization of trips could be practice. It also illustrates the benefit of having one "flexible" schedule, combined with some fixed routes.

Introducing flexible route(s) would be on the expense of some fixed routes. By investigating the set routes from the first solution, we can determine which routes to remove by looking at which once has the least effect on the demand. Removing route k2 has slightly no effect on the overall result, still maintaining a cover-rate of 99 %. Removing additionally route k19 and k12, leaves the coverage rate on 88 %. The four remaining routes visit all five locations, and does not deteriorate the passengers travel times. However, frequency will reduce at some nodes due to the limitation of ferries. Introducing a flexible route, the coverage-rate and frequency would again increase. A solution could also be to have one ferry that operates only in the peak time, hence from 07:00-08:00 and 15:00-16:00. Employing people to work shifts for one hour, could again raise other concerns.

¹where (16) indicates $l = 16$

5.1.1 Demand Uncertainty

All other things being equal to the previous section, I will present the case with changed demand. The reason behind these adjustments are as described in Chapter 3.3. Due to increasing technology and innovations within i.e. transportation, we can expect greater access to the origins. E.g. because people have access to city bikes/scooters and can reach the respective destinations easier than if they were to walk. Additionally, we can expect tourists to see more of the city than just the city center and therefore prefer to use the BLR as a sightseeing opportunity. This trend has been shown in other cities providing similar ferry-services, such as Amsterdam and Brisbane. On the other side, expected demand can be significantly lower than the first run, and the "worst-case" scenario will be tested accordingly. The reasons for this demand can be that the expected passengers prefer to use other transportation or that it takes time for people to adjust their travelling habits.

As the model doesn't consider ferry-capacity, increasing the amount of passengers have negligible impact on the results. One should however bear in mind that if demand is higher than expected, the assumption of kept capacity might not hold. For example, during the max-hour from 07:00-08:00, a 20 % increase in demand implies an average of 29 passengers per 15 minutes from Sandviken 2 to Strandkaaien. If the ferries have a capacity of 40, and a route includes multiple stops, the risk of capacity issues arise. Thus, passengers will have to wait for the next ferry to arrive, which can cause customer dissatisfaction. As earlier mentioned, the BLR is meant as a supplement to the existing public transportation, and for the passengers traveling from Sandviken - Strandkaaien, there are numerous options. Therefore, although a direct route between the respective pickup and delivery-locations would be a solution to the capacity-issue, it might be unnecessary due to the number of other options. However, if passengers experience this issue frequently, they might lose trust to the service, and hence expect it to be full at all times.

Reducing demand by 10 % has barely any impact on the result. This makes sense as the lowest required pickup-amount is set to 5. Thus, as long as the passenger groups are ≥ 5 , the results stay constant. Consequently, there are two ways to obtain different solutions: (1) increase θ ; (2) reduce demand to critical amount is reached, where the amount reduces from $\geq \theta$ to $< \theta$. Reducing demand further, addressing the worst case, reduces the

optimal solution to a total of six routes divided on 327 passenger in total. Thus, 55 passengers per ferry for the respective 3 hours. These routes is similar to the solution from the first solution, with route k5 being different. k5 is a direct route from Sandviken 2 to Strandkaien. Considering time, passengers on this route have a variety of indifferent transportation options as the sea distance is similar to road distance on this particular destination. As the BLR is meant as a supplement to the existing transportation, it is still a question if such a route should be an option. An argument would be that these routes are effective, and a ferry could obtain high profits if this route fulfills high demand. Assuming ticket prices are equal for all passengers, it could be beneficial to include a route from Sandviken 2 to Strandkaien as a buffer to gain fast profits. To evaluate the value of k5 for this purpose, I set $\theta = 0$ such that all demand is considered. For the worst-case scenario, k5 can transfer 65 passengers from 06:00-09:00 with a total of six trips. Hence, between 10-11 passengers per trip, each with a duration of 11 minutes (incl. service time). Accounting for these passengers can imply an efficient option for the operation to gain profits, however it does not fully cope with the intention of being a supplementary transportation option. Therefore, such an option should be considered as an additional route if capacity allows it. Furthermore, the demand for it might be worse than expected, as the alternatives such as bus is already sufficient both considering time, price and comfort. Further discussion will be implemented in Chapter 6.

The solution for the worst case scenario presents six routes. Further insights disclose that removing k19 have negligible effects on the result, retaining a coverage-rate of 93 %. The remaining routes are k1,k5,k7,k9 and k12. Assuming that k5 is unnecessary due to the passengers having indifferent alternatives, only four routes are needed. Nevertheless, route k1 still provides direct alternatives for the passengers from Sandviken 2 to Strandkaien, but departs less frequent as it also includes Sandviken 1. As we expect a higher amount of passengers between 07:00-08:00, analysing exactly when the four routes are needed can reduce number of required service time further. The last hour, from 08:00-09:00 is not effected by removing k12. By removing thi routes the last hour, we thus maintain the 93 % coverage-rate. What more, an insight on the traveling times for the passengers reveal some interesting observations. Passengers from Sandviken 1 and Sandviken 2 to Nøstet and Strandkaien can expect travel times between approx. 11 and 21 minutes. The latter being from Sandviken1 to Strandkaien, which could be seen as a critical time, as

the distance can be covered with shorter traveling time by public transportation or car. This does not account for all passengers from Sandviken 1, as walking distance to the pickup-location should be considered. Moreover, other public transportation should be accounted for traveling time to/from e.g. the bus stop, compared with the corresponding time to/from the ferry-depots. This is beyond the analysis provided in this thesis, but can be something to discover in further research on the BLR. Furthermore, passengers from Laksevåg to Sandviken 1 and Nøstet can be transported directly using route k12 and k7. If they're destination is Sandviken 2, the shortest travel time is 20 minutes, having a transit-stop at Sandviken 1. From Laksevåg to Strandkaaien however, the passenger can expect a travel time of 32 minutes. An alternative solution is to join the direct trip to Nøstet, depending on where they are heading. The OD-pair from Laksevåg to Strandkaaien are however not considered in this solution as they are less than θ .

5.1.2 Modifying Parameters

Testing the model further by changing all constants, the solutions vary. Moreover, I will present the most interesting findings from all runs. Experimenting with different values for the constant parameters: β_d , θ and T_h^{start} and T_h^{stop} . As earlier, a β_d of 15 minutes, would mean that a travel time of 10 minutes, in reality could mean 25 minutes, hence 150 % increase. Therefore, a lower patient can be expected in reality without further analysis. This especially accounts for short-distance travels as the BLR offer. It is reasonable to believe that a patient of 15 minutes is more realistic for trips of i.e. an hour, as 15 minutes only increases the total travel time by 25 %.

Lowering β to 5 would be more realistic. By doing so, ten routes are required for the worst-case scenario. Increasing demand to the highest expected from the search-criteria in the data section, this amount increases to 12 routes. In addition, the 12 routes requires multiple ferries to fulfill the frequency demanded. For example, route k5 should depart every fifth minute on its 11 minute route - requiring multiple ferries. The reason is the required frequency at each stop by implementing the low patient. Without further investigation, it is reasonable to believe that these criteria is expensive to fulfill. To compensate for the low patient, a high θ can be implemented. Thus for OD-pairs with high number of passengers, a higher frequency can be tolerated. With a $\theta = 15$ the solution provides seven routes. This for a total number of 319 passengers. The routes required

to fulfil this demand is k1, k5, k7, k12, k16, k17 and k18. However, it requires route k5 and k16 at a higher frequency than possible with only one ferry assigned to the routes. That being said, reducing to one ferry each route, 77 % of the demand is still covered, thus 246 passengers. What more, including only the five routes that fulfill demand for the highest amount of passengers, 65 % of the demand is fulfilled. To investigate the amount of passengers utilizing these routes, θ is removed. This disclose 338 passengers will use the service for the respective time horizon.

Adjusting θ provides interesting insights as it accounts for more "mainstream" demand. Targeting these passengers could be beneficial in the start-up phase for the service, as it could require less investment costs focusing on only a fraction of the OD-pairs. In addition, it can be easier to provide a lucrative service for those it is targeted towards. Meaning that this would mean less origins and destinations, and thereby routes with less multi-stops which in turn will provide a higher frequency and passenger satisfaction. With $\theta = 15$ the delivery-locations are limited to include only Strandkaien and Nøstet, which makes sense as the distribution in the morning hours are generally towards the city center. On the other hand, the high number of passengers in a OD-pair is only to find in passenger groups going from Sandviken 2. Thus, Laksevåg is not considered at this point, which raises some concern. The distances from Laksevåg to the city center and Sandviken is the ones that assumingly generates the highest benefit from the BLR, as the difference between sea distance and road distance are highest. Experiments with different values for β and θ are presented in table ??, including both expected and worst-case demand. In addition, $[t_{start}, t_{end}]$ represent the time period for each run, included in order to investigate patterns for high-demand periods.

Table 5.1: Modifying Parameters

Demand	β_d	θ	$[t_{start}, t_{end}]$	$K \in G$
Expected	15	5	06:00-09:00	k1,k2*,k7,k9,k14,k19
Expected	5	15	06:00-09:00	k1,k5*,k7,k12,k16,k17,k18*
Expected	5	10	06:00-07:00	k1,k5,k9,k18
Expected	5	10	07:00-08:00	k5*,k7,k16
Expected	5	10	08:00-09:00	k1,k5*,k7,k10,k16,k18
Expected	5	10	07:30-08:30	k5,k7,k14,k17
Expected	5	15	06:00-07:00	k1,k16,k18
Expected	5	15	07:00-08:00	k5,k7,k16,k17
Expected	5	15	08:00-09:00	k5,k7,k16
Expected	10	10	06:00-07:00	k1,k5*,k9,k14
Expected	10	10	07:00-08:00	k5*,k7,k16
Expected	10	10	08:00-09:00	k1,k5*,k9,k10,k16*
Expected	10	10	07:30-08:30	k1,k5,k7,k16
Expected	10	15	07:30-08:30	k1,k5,k7,k16
Worst-case	15	5	06:00-09:00	k1,k2,k7,k8*,k12,k14,k16
Worst-case	5	15	06:00-09:00	k5,k7,k12,k14,k16
Worst-case	5	10	06:00-07:00	k1,k8
Worst-case	5	10	07:00-08:00	k5,k7,k16,k17,k45
Worst-case	5	10	08:00-09:00	k5,k7,k16
Worst-case	5	10	07:30-08:30	k5*,k7,k14,k17
Worst-case	5	15	06:00-07:00	no passengers
Worst-case	5	15	07:00-08:00	k5,k16,k7,k14
Worst-case	5	15	08:00-09:00	k7
Worst-case	10	10	06:00-07:00	k1,k9
Worst-case	10	10	07:00-08:00	k5*,k7,k16
Worst-case	10	10	08:00-09:00	k5,k7,k16
Worst-case	10	10	07:30-08:30	k1,k5,k7,k16
Worst-case	10	15	07:30-08:30	k5,k7,k16

*Higher frequency at route required height

Adjusting time periods reveals some interesting observations. Despite 07:00-08:00 is time where demand is at it's peak, it is not necessarily the period requiring most routes. One reason is that passengers demanding to be at their destination at 08:00, allows for delivery β minutes earlier, and thus they are considered in the time interval [08:00, 09:00]. Testing the time interval [07:30, 08:30] confirms this theory. Furthermore, splitting the time horizon by hours, the results show that in most cases, four routes seem sufficient. The main issues arise when the model is assigned to choose routes to operate for a long period with a range of different demand. However, splitting into shorter periods to maintain different results means that the routes should no longer be fixed. Constructing routes that allows to change during the hours could therefore be a solution to limit the number

of ferries operating.

5.2 Ferry Network Flow - Noon Distribution

The situation concerning number of routes could vary significantly during the day. This due to passengers' daily agenda and lifestyle. Workers and students tend to dominate the morning peak, and are great contributors to the afternoon peak as well. Besides these periods, passengers travel to appointments, meetings, field trips, etc. Around noon is a period characterized with low demand, based on distribution patterns from real bus-data (COWI, 2015). Similar to the latter section, I will analyse and present the ferry network during the time interval [11:00-13:00].

Likewise to the morning distribution, β_d is first set to 15, $\theta = 5$ and T_h^{start} and T_h^{stop} is set to 11:00 and 13:00, respectively. During the first runs, demand is also set to expected. Consequently, correlation between the two periods can be discovered. As expected, less routes are required, with a solution of four routes, divided on 96 passengers. These are: k5, k7, k9 and k14. Applying these routes to all passengers within the time period (for $\theta = 0$), 64 % of all passengers are covered. Insights to the allocations however, reveal that there are only passengers from 11:00 to 12:00 being considered. Passenger flow after 12:00, to 13:00, is below the limit of $\theta = 5$. Furthermore, experimentation with the chosen routes reveal that excluding either k14 or k5 reduces the coverage-rate by only 17 %. As mentioned, k5 is a direct route between Sandviken 2 and Strandgaten, a distance which have approx. same length by sea as by road. In addition, alternatives for these passengers are many, as well as frequent. Moreover, route k14 includes the same nodes as route k5, in addition to Laksevåg. Whilst the routes fulfill demand for an equal number of passengers, excluding k5 could be more valuable in the long-run. As the distance between Sandviken and Laksevåg is remarkably shorter across sea than by road, it is reason to believe that passengers on this distance appreciate high value of the service. Whereas passengers from Sandviken 2 to Strandkaaien chooses whatever transportation that fits the need when it occurs, that being the BLR, the bus or the nearest city bike. On the other side, the shorter traveling distance per passenger, the more costs saved, assuming that ticket prices are equal for all distances. Thus, route k5 can seem lucrative from an operational perspective in the short-run.

Periods with too low demand raises concerns whether service should continue, or if operations should be limited to the most demanding periods. It is estimated a total of 171 passengers throughout the two hours, where a combination of the three routes k7, k9 and k14 can cover for 110 passengers. This means slightly below 37 passengers per ferry, and less than 4 passengers per trip. Whilst a taxi-service would find these numbers sufficient, it might not be for a ferry with a larger capacity and higher operational costs. Changing the objective to minimize number of trips we gain that only 8 trips is required, being within the routes k5, k18, k7 and k9. In order to fulfill all demand however, route k5 needs to depart with a higher frequency, the same accounts for route k18 requiring two ferries for each. By expanding the patience for passengers to $\beta = 20$, the frequency thus reduces the objective function to four trips, during the two hours, as more passengers can be picked up by less ferries. In reality, it is optimistic to believe that people have this patience considering the availability of other options. That being said, in some scenarios, people might be indifferent whether they arrive at 11:00 or 11:15, especially when they do not have a strict agenda, and they might prefer the BLR for other reasons than traveling time and punctuality.

Furthermore, during a period where demand is low, there might not be need for a supplement as the BLR. Thus, operating around the busiest times a day would be sufficient. As earlier mentioned, an option can be to have set routes for the busiest times, and then have a more flexible route when there are no clear demand pattern. Only concerning the period from 12:30-13:00, with $\theta = 2$, only one trip is necessary, within k9. For the period 12:00-12:30 the majority of passengers are going from Laksevåg or Sandviken 2 to Nøstet, making route k18 and k16 prominent. Running the model with a $\beta = 15$ and $\theta = 2$, these routes alone are not sufficient, as they have a long duration and therefore low frequency. This means that increasing the number of nodes in a route is not necessarily effective. What more, with a low frequency passengers might prefer other transportation modes due to higher convenience. That being said, maybe even direct routes for low demand periods is more efficient. E.g to have one route from Sandviken to Laksevåg and another from Nøstet to Laksevåg. Route k5 appears in solutions, as demand between the two nodes are always present. The frequency of the route makes it able to transport people with a range of different demanded arrival times. This also accounts for people having low patience, and could contribute to high passenger satisfaction. Having

direct routes between all nodes is not a realistic solution. If the routes should be exclusively direct routes, then a selection would be necessary. During the low demand periods, a route between Sandviken 2 and Strandkaaien appears to be lucrative. However, direct routes from Sandviken 1 or Sandviken 2 to Laksevåg, seldom appears as a solution. Therefore, direct routes between the shortest distances seems more prominent than direct routes between long distances. In fact, combining Nøstet in a route from Sandviken does not increase the time of that route in a significant manner, whereas adding an additional node to route k5 would at least double the duration of the trip, regardless of which node. Route k10 however, is a direct route between Laksevåg and Nøstet, and has relatively low duration, likewise to k5. That being said, the demand for this route is more present during the morning- and afternoon-peak, as people mainly travel this distance to/from work and universities. Therefore, during a low demand period, having a direct and high-frequency route where demand is more present could be a possible solution. The benefits of this is to continue operations and still fulfill demand for a sufficient number of passengers.

5.2.1 Demand Uncertainty

Investigating the worst case scenario by analysing the passenger distribution table disclose a significant low demand. The first 30 minutes of the time horizon includes passenger groups with more than 5 passengers. During the last hour, the demand is near to non-existent. Setting $\theta = 2$ reveal a requirement of eight routes. Experimenting with these brings to the conclusion that route k5, k9, k14 and k17 covers 84 % of the respective demand, accounting for 83 passengers. Due to low demand, a higher θ would mean that there will not be need for any routes operating. To continue operations, it is therefore a question whether a pickup of less than 5 passengers per stop is worth the costs of operating. This raises concerns whether the BLR should start it's operations as a supplement exclusively in the peak hours. As mentioned in the previous section, analysing the possibility for routes with lower duration, targeting only the highest demand, could be favourable in these situations, in particular.

5.3 Ferry Network Flow - Evening Distribution

The evening distribution starts at 15:00, meaning the peak from 15:00-16:00 is included. It makes sense to split the distribution in periods. First of all because the peak from 15:00-16:00 should not bias the entire period. Secondly as the distribution is somewhat similar to the morning distribution, where we experienced great improvement by dividing the time horizon by hours. The differences between the two distributions is that this period begins with a peak and reaches a minimum between 17:00 and 18:00 and thereafter increases. Thus, we can expect demand to increase during the evening, but reaching a minimum between 17:00 and 18:00. These thoughts taken into consideration, an analysis with varying demand and parameters is presented in table 5.2 below.

Table 5.2: Modifying parameters

Demand	β_p	θ	$[t_{start}, t_{end})$	$K \in G$
Expected	5	5	15:00-16:00	k1,k5,k12,k16,k17*,k18
Expected	5	5	16:00-17:00	k1,k5,k7,k16*
Expected	5	5	17:00-18:00	k12,k18
Expected	5	5	18:00-19:00	k1,k5,k9,k12,k16
Expected	5	5	19:00-20:00	k1,k5,k17,k18,k16
Expected	5	10	19:00-20:00	k14,k17,k18
Expected	5	10	18:00-19:00	no passengers
Expected	5	10	17:00-18:00	no passengers
Expected	5	10	16:00-17:00	no passengers
Expected	5	10	15:00-16:00	k1,k12,k16,k17,k18
Expected	5	12	15:00-16:00	k1,k17*,k18
Expected	10	5	16:00-17:00	k1,k5,k7,k16
Expected	10	5	17:00-18:00	k1,k9
Expected	10	5	18:00-19:00	k1,k5,k9,k12,k16
Expected	10	5	19:00-20:00	k1,k5,k17,k18
Expected	10	10	19:00-20:00	k5,k7,k18
Expected	10	10	15:00-16:00	k1,k12,k17,k18
Expected	10	12	15:00-16:00	k1,k9,k17
Worst-case	10	5	15:00-16:00	k5,k12,k17,k18
Worst-case	10	5	16:00-17:00	k7
Worst-case	10	5	17:00-18:00	no passengers
Worst-case	10	5	18:00-19:00	no passengers
Worst-case	10	5	19:00-20:00	k1,k5,k17,k18
Worst-case	10	10	19:00-20:00	no passengers
Worst-case	10	7	19:00-20:00	k5,k18
Worst-case	10	3	16:00-17:00	k1,k5,k7,k16
Worst-case	15	5	15:00-16:00	k1,k5,k9,k18
Worst-case	15	5	16:00-17:00	no passengers
Worst-case	15	5	17:00-18:00	no passengers
Worst-case	15	2	17:00-18:00	k5*,k7,k9,k17
Worst-case	15	5	16:00-17:00	k1,k5,k9,k18
Worst-case	15	5	19:00-20:00	k1,k5,k7,k9
Worst-case	15	10	19:00-20:00	no passengers

*Higher frequency at route required

Limiting the criteria we see that the period from 16:00-18:00 contains no passengers. On the other side, with low passenger patience, β_d and low demand requirements for the ferries, many routes can be assigned to a low number of passengers. However, having these low criteria, requires up to six routes for the peak hours, some including additional ferries to gain higher frequency. From a passenger perspective, high frequency and delivery as close as demanded arrival time as possible would be preferable. For taxis or low-capacity

transportation, this is also feasible from an operational perspective. However, in the long run, it would not make sense for ferries serve between one and five passengers each trip. Considering the uncertain demand, these trips might even be without passengers in reality. On-demand services could solve this issue, as ferries would only operate under certainty, and would only pick up passengers when sufficient demand is present. This will be further discussed in Chapter 6.6. As the BLR doesn't operate on-demand, situations with empty ferries might occur, but assigning routes where expected demand is near zero, is unreasonable. Therefore, targeting high demand, would reduce risks and maintain a sustainable business. Sustainable in the sense that the BLR would gain profits by serving multiple passengers simultaneously and thereof survive as a business. To gain further value for the passengers, some routes could operate also in low-demand periods. From table 5.2 some routes have higher appearance, such as k1, k5, k17 and k18, for both cases of demand. Running the model with the four mentioned routes for the expected demand and patience $\beta_d = 15$, 73 % of the demand is covered. Restraining to $\beta_d = 10$ and 5 reduces this coverage-rate to 62 % and 32 %, respectively. Only applying the routes to the peak hours, being from 15:00-16:00 and 19:00-20:00 they cover 38 % and 55 %, respectively, with $\beta_d = 5$. If the passengers patience is increased with additional 5 minutes, the coverage rates is increased to 83 and 74 %. Thus, from 15:00-16:00 increased patience shows clear effects on the results. It is furthermore crucial to mention that passengers might prefer to arrive earlier than demanded arrival time, depending on their end destination - being the reason why the passenger needs to be transported. This could be either work, shopping or a dentist appointment. Hence, passengers might prefer an earlier arrival due to additional time to get to their end destination. Patience also depend on individuals, as some prefer to be early regardless of what the agenda might be, and others who prefer to be precisely on time, even a couple minutes late could be preferable for some. Passengers with no appointments, e.g. tourists on sightseeing, will adjust to the set schedules, thus have a longer patience.

Furthermore, during the period with low demand, from 16:00-19:00, it depends whether it is sustainable to operate. Setting a high θ reveals the negligible demand and that even in some scenarios there are no passengers. For the expected demand and $\theta = 5$, some route k1, k5 and k16 appears to be of high value, due to their presence in multiple runs. A

quick analysis of the three routes reveal that they cover for 44 % of the demand, both for $\beta = 5$ and 10. Minimizing number of trips during this period, introducing more flexible routes, is a solution to increase the cover-rate without going on the expense of additional ferries. Running the model however reveals that one trip per passenger group is needed, due to longer time-span between demand.

Further insights to the trips disclose that they cannot be combined due to overlapping time. An interesting insight is however that the majority of trips are within k5 and k18, leading to a new analysis for the respective routes. The two routes alone can in the period cover demand for 42 %, and increasing frequency further increases this rate. k5 and k18 does not cover passengers going to Sandviken1 due to its low expected demand. This raises questions whether the service should be limited to only a fraction of the nodes in low-demand periods. In addition, changing route k5 to k1 is a solution to maintain service on all nodes. However, this reduces frequency between the more demanding nodes. Furthermore, passenger groups from/to Laksevåg after 16:00 all include less than three passengers per 15 minutes. Including routes going continuously to/from Laksevåg after 16:00 could therefore mean higher expenses than revenues. That being said, the distance between Nøstet and Laksevåg is less than 5 minutes. Including Laksevåg in the route between Sandviken 2 and Nøstet (i.e. k18) doesn't go on the expense of the passengers from Sandviken 2 to Nøstet. Therefore, route k18 can be valuable for such low demand periods, even though it excludes Sandviken 1.

The evening distribution includes both high and low demand periods, which highlights the effect of operating at only specific times. As the BLR is meant as a supplement to the existing public transportation in the city, it is not unreasonable to restrict service time to the more demanding periods, thus when the majority of people travel to/from work and universities as well as during the late evening. Due to uncertainties considering demand, capacity, transportation trends and consumer behaviour, the results presented throughout this chapter should only provide guidance to the research on the Blue Light Rail. The limitations as well as the value from the model and approach utilized in this thesis will be discussed throughout Chapter 66.

6 Discussion

Speranza (2018) claims that one of the main reasons that lead people to use their own vehicles as a result of lacking flexibility of mass transit systems. In particular mobility systems with high travel time and low frequency is a critical issue. Supplying the transport system in Bergen with a electric-driven ferry transportation, will increase robustness and flexibility to the overall transportation offer in the city. The analysis provided in this thesis, aims at how this service most efficiently can fulfill demand between the five provisional depots provided. The analysis is based on a set of fixed and pre-set routes, and tests how results change due to change of assumptions. The solutions show that during periods with clear patterns, such as in the peak hours from 07:00-08:00 and 15:00 and 16:00, fixed routes with three or four depots is lucrative. From an operational viewpoint, adding multi-stops can be favourable as it can fulfill demand for a higher number of passengers within shorter time. This is also supported by An & Lo (2014), who further claims that such multi-stop trips might decrease passenger satisfaction. However, to provide service for all estimated demand within the periods with high demand requires either multi-stops or more ferries to increase frequency, which can in turn create high costs. What more, for the routes including only three depots, a passenger only risks one intermediate stop. In high-demand periods, direct routes could be rather inefficient, as including additional stops will most effectively pick up passengers at their origins and collectively bring them to their designated destinations. This would go on the expense of travelling time for passengers, but provide service to a higher number of passengers.

As the BLR is meant as a supplement to the existing transportation, it is questionable whether operating at low-demand periods is requisite. Moreover, the BLR can risk situations with close to zero passengers, raising concerns whether it should limit its operation to the peak-hours. After a thorough examination, some solutions were identified. Route *k5*, which is a direct route between Sandviken 2 and Strandkaien, seemed to be a route with sufficient demand even in the low-demand periods. Whilst the travel time on this direction will be fairly similar to the travel time by road, and there are frequent opportunities using bus-services, it is questionable whether there is demand for an additional transportation offer. That being said, travel time is not exclusively the criteria when choosing transportation mode. Fare-prices, frequency, punctuality, comfort

and other factors also come to play. According to Yu et al. (2015), in terms of public transportation convenience, and to meet passenger needs, the service frequency should be as high as possible. Providing direct routes will be a solution to provide this frequency, or introducing multiple ferries. In periods where demand is low however, it seems to be beneficial to operate with one or two direct routes. What more, route $k18$, being a route with three stops, seemed to provide high value in terms of fulfilling demand. Selecting particular OD-pairs in low demand periods, might be a solution to meet both operational and passengers interests. as the total travel time will increase with each intermediate stop.

Dividing the time horizons in shorter periods, it was interesting to find that operating with set and constant routes throughout the time horizon was an inefficient solution to the problem. Thus, the results indicated that the solutions could reduce flexibility, if not increasing the number of required ferries. Dividing the time horizons to hours, it came clear that adjusting routes throughout the day would benefit the operation, as well as fulfill more demand. Another solution is to operate with some fixed routes where there are clear patterns, and have one flexible route that aims at fulfilling the excess demand where patterns are less present. However, due to highly uncertain data, constructing routes based on periods with low demand and low patterns, can create some risk. Thus, creating schedules in periods where a supplement is more needed, i.e. the peak hours, is a reasonable start for the business. This can gain a reputation and build the passenger base, and thereafter operations can expand their operating hours.

In near future, uncertainty might be solved with innovations allowing for on-demand services. In the following sections, I will provide a discussion for further improvement to the analysis and approach which I have conducted in this thesis. Furthermore, I will in short discuss opportunities and concerns new technology and digitization bring to the transportation sector.

6.1 Model Improvements and Further Research

The model which this thesis presents, provides insights concerning the uncertain information we have to date. It proposes an intuitive approach to be used for scenario analysis on demand and routing-analysis. The decision variables are the number of routes

and trips chosen and uses a column generation method to solve the minimization problem. The approach can be adopted to other cases where similar analysis is required due to high uncertainty. E.g. when investigating other similar networks, both on land and at sea. Other examples are by airline operations, and rescheduling. The approach of matching passengers to routes could also be useful in re-allocating passengers to new flights in case of delays. By using already set timetables and historical delay-data, one could easily use the approach to allocate passengers to alternative flights, if such flights exist. Another implementation of the approach can be in assignment problems where employees need to be assigned to projects and one should determine how many employees needed to fulfill all projects within certain time frames. That being said, it could in general be adopted to cases with limited and small data-sets, as big data-sets would require more computational power than is for the case presented in this thesis. The approach and model could still be improved and used as inspiration similar cases.

Furthermore, the model could be improved to consider the minimization of time and/or costs. As the model includes set schedules and routes, and aims to find the least number of required routes, the total duration is not fully optimized. For further research, it would be interesting to analyse how the schedules would look like if the model itself could create schedules based on demand. This aligns more with a typical NDP. E.g. the representation of a ferry network which is proposed by An & Lo (2014) differs from the representation which have been proposed in this thesis. Using nodes and arcs is usually favorable if you would identify all possible combinations of nodes and all possible directions between them, thus all route combinations. What more, this would provide more flexible routes, concerning demand at all times during the time horizon. For a case where demand is certain, it would be interesting to see results using this approach. From an operational perspective, this approach can be targeted to save costs, as the routes would be set such that all trips provide value. With pre-set schedules, the solutions suggested from the model might include a route where only one trip is necessary for that particular route to be included. Therefore, more thorough analysis have been made, e.g. by splitting the time horizons to check the differences between them. For a longer time horizon, such an approach would be time demanding, as it requires more insights to the results made. Similar to the ferry network design by An & Lo (2014), the node and arc representation is extensively used in transportation and routing problems (Furtado, Munari & Morabito,

2017; An & Lo, 2014; Yan et al., 2013), due to the convenience of investigating all possible solutions in a transportation network. Passengers may however, prefer structured and logical schedules. This could however be implemented as a constraint indicating frequencies at each depots, e.g. that a ferry visits Sandviken 1 every 15 minutes. Moreover, pre-setting routes have the benefit of providing structure and thereof predictability for the users. Due to high uncertainty on data, making routes solely depending on demand would decrease validity. Scenario-analysis or simulation should be practised when working with high uncertainty. That being said, for further analysis, and for similar cases with more certain data, using a NDP as presented by An & Lo (2014) could gain useful insights that can further enhance the robustness and flexibility of the BLR. In addition, both approaches could complement each other. First, pre-set routes can be made in order to make structured schedules for the mainstream demand, e.g. these routes should cover for 70 % of the overall demand. Thereafter, the general NDP could be utilized to make one or two flexible routes that cover for the remaining demand.

The ferry network analysed in this thesis has a range of yet uncovered questions, such as locations, demand, routes and amount of ferries required. Due to this, a range of assumptions and estimations are included, and the analysis is based on a diverse scenarios for demand and time windows as well as distribution of demand. Three years from now, this scenario would look different and using real data for analysis will be possible - given that operations starts. In this case, the results from the model would look quite different, and as the routes have then been tested, more qualitative and quantitative data can be provided. Analysing improvements to the ferry network design will then be present, including passenger waiting time, robustness in case of delays or introducing additional locations for ports might be a question. Looking back at the literature, there is a range of inspiration to how these analyses can be approached. In addition, modifying the approach which this thesis provides can be useful for similar analyses. By adding further constraints due to capacity, patient for passengers as well as defining passengers having different weights.

Furthermore, it would be interesting to see how the results would change due to real data on-demand. This would then include abnormal travel patterns such as people working night shifts or people demanding to be sailed from e.g. Strandkaien to Nøstet despite the

travel time it includes. with no further modification to the model, this would generate some unsatisfactory results. This due to the assumption that all passenger groups are equally important. With the current operation, it wouldn't be logic to treat 20 passengers going from Sandviken 2 to Strandkaaien equally as 1 passenger going from Nøstet to Strandkaaien at the same time. In this case, the assumption would be that not all passengers are equally important, and thus prioritize passengers that will gain higher profits or make sense for the operations in a long-run. Using an more advanced algorithm for entropy maximization and expected passenger utility, as introduced by Bell et al. (2019) could introduce useful insights from a passengers perspective. Moreover, it would increase the service value provided, by increasing customer satisfaction. This case excludes the operational view and focuses mainly on the passengers, which is sufficient for the analysis, but might not be implemented in reality. Another example than entropy would be to add a penalty for a certain "type" of passengers under the objective to minimize travel distance or operating costs. For example, adding a penalty for abnormal demand would increase distance or costs such that the model would choose passengers providing the least penalties. Adding penalties is an extensively used solution to target the objective, and can be used not only for the latter case, but also for i.e. time. When e.g arrival times are feasible, but undesirable, adding a penalty can be introduced to address the issue (El-Sherbeny, 2010). In the cases where passengers have abnormal demand, it could also be that they should be accounted for, but they might not get a desired travelling route. E.g. there is a feasible solution for their required pickup- and delivery location, but they might have to accept that it goes on the expense of that particular passengers patient. Another instance where this solution occurs useful is when prioritizing routes. The BLR is meant as a supplementary passenger transportation service, and thus aims not to compete with i.e bus, the light rail or city bikes. transporting people from Inner to Outer Sandviken is therefore not a goal itself, as these passengers have a range of options that is equally or more efficient and costly. This also accounts for the two locations in Laksevåg. This being said, prioritizing passengers that have a significant benefit of using the BLR should be higher prioritized.

Including minimum travel times for the passengers could be a supplement to the model. To do so, a qualitative analysis on the users' travel-pattern and behaviour should be conducted. As a consequence, a time window indicating earliest time of pickup and latest

time of arrival would be allocated each passenger group. The model would then provide better views from the passengers perspective. Although the approach presented in this thesis presents routes that in general provide low travel times for the passengers, and sees the passenger view in terms of patience - and the maximum of two intermedia stops, there are still ways to increase passenger satisfaction. As Yu et al. (2015) mention in their research is the costs for passengers, as well as the operator. They further aims to find the optimal balance of interest between the operators and passengers in a waterbus system (i.e. "ferry network"). They therefore let some wasting of resources and thus rising operating costs take the expense of increasing service. By introducing ticket prices and operation costs, this could be further investigated and implemented as constraints to the model. Similarly, Lai & Lo (2004) tries to account for the conflict of interest between the operator and passengers. This article approaches shortest-path algorithms and solves scheduling and passenger loading in an efficient manner. In other cases, two-way heuristic algorithms is used for this matter, which tries to optimize the interests from the two interest parts. The methods of Lai & Lo (2004) could be helpful in reducing passenger waiting times as well as improving efficiency for further service for the BLR.

6.1.1 Development in Information and Transportation Technology

The explosion of Big Data has changed the landscape of transportation research. The technical advances in remote sensing and communications channels have substantially increased the quantity and quality of available information. In the era of Big Data, travel times can be estimated much more accurately by machine learning and deep learning approaches and updated dynamically; faster algorithms and more powerful hardware will allow "real-time" planning and dispatching. This may strengthen the need for dynamic and deterministic on-demand models, especially when the impacts of the sources of other uncertainties are rather negligible. The trend may shift research on solution methodologies to focus more on fast on-line algorithms for dynamic and deterministic models to facilitate "real-time" re-optimization. That being said, the advancement of information and communications technologies can impose a tremendous computational burden on the delivery of solutions due to several reasons, such as a very frequent re-optimization necessitated by continuous information updates from multiple sources.

For the case of the BLR, we need to consider demand to generate routes. The purpose of this thesis is to analyse which fixed routes that is favourable, and to create schedules passengers can relate to and understand. Another method is to create more flexible routes where the ferries can operate on-demand, or a case where some of the ferries have fixed routes and one of them has a flexible route that can fulfill exceeding demand or abnormal demand. On-demand operation is extensively researched and closely related to the dial-a-ride problem, addressing the demand-responsive shared-ride systems. The dial-a-ride problem is mostly researched on road-traffic, but could also be implemented to seaborne transportation. In concerns of unavailable hours or low demand periods, an on-demand service could be of value. However, requiring employees to work only when there is demand, thus under high uncertainty, could be a difficult task. That being said, sharing services such as Uber and Lyft has solved this issue. Implementing this solution to waterborne transportation is not practice, as people don't use their boats as their cars. Nevertheless, being aware of the innovations that will change the means of how we move, can be an eye-opener in the search for new city-development to further increase the flexibility and robustness of the transportation offer.

For future purposes, we might experience technology that reduces the need for fixed routes as presented in the model. With autonomous ferries and transportation, the ease of providing on-demand services increases. Autonomous ferries will have the benefit of providing service at all times, with no need for employees taking breaks or time off due to low demand. With less, or even no, employees, the operational costs reduces and thus, less passengers are required to earn profits. Integrated service can reduce the operation cost and increase utilization of the ferries. However multiple transfers may be a problem, leading to long waits and passenger discomfort. This type of mixed-mode operation is being considered by many public transit authorities, and also points to new research directions for the dial-a-ride problem. It is an interesting topic which may be case for the BLR for the years ahead, but for now, this is only a topic of discussion.

7 Conclusion

Technological development, urbanization and a green-strategy has raised concerns for new developments in the city of Bergen. The goal for zero growth in private transportation and a vision of zero emission within the year 2030, as well as visions to reduce congestion and inner-city traffic requires solutions beyond road transportation. Moreover, increasing supply of transportation alone is not sufficient to meet a growth in transportation.

During the autumn of 2017, the city council of Bergen presented the idea of a "Blue Light Rail" between the city's districts and close municipalities. European cities, such as Copenhagen and Amsterdam, have already developed electric ferry solutions for passenger transportation. These services have increased flexibility and robustness to the overall transportation offer in the cities. In addition, many cities have experienced these ferries as a driver for tourism. Throughout this thesis the prospects for an electric ferry service in Bergen has been presented, analysed and discussed. In addition to low emission, the ferries can easily access areas that are generally difficult for existing road transportation. Nevertheless, there are still questions unanswered. Due to Bergen's population of approx. 284 000, high uncertainty on demand and traffic base is present raises risks for starting operations. Moreover, this thesis has provided a modelling approach to investigate how such a waterborne passenger transportation can gain value to the overall transportation offer in Bergen. By experimentation of different scenarios and distributions of demand, a picture of how the service could work in reality have been painted.

The model made in this thesis is based on the ferry network design problem with pickup and delivery (FNDPPD), as it concerns a fleet of ferries transporting passengers from their designated origin and destination. Due to the high uncertainty and lack of data, testing the model with different demand scenarios have been conducted. Fixed routes were pre-set and the objective function aimed at searching for a combination of routes that required the least ferries operating. Analysis revealed that in cases with low demand, routes with high frequency, targeting only selected passenger demand would be a solution that maintains value both from an the operator and passengers viewpoint. However for high-demand periods, it should be evaluated whether the operations should focus on the distances where the BLR could supply as a faster solution than the existing transportation.

Thus, from Laksevåg to the city center and Sandviken. Different perspectives have set base for the analysis, which have shed light on some of the possible outcomes a Blue Light Rail will have for the city of Bergen. In addition, the discussion raises concerns for innovation and technology that will change the means of how we move. Increased environmental concern and digitization is a combination that can result in tremendous change within the era of transportation, and electric ferries is only the beginning of Bergen as a "smart-city".

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Appendix

A Population divided on selected area zones

The documents presented in this Appedix is conducted by the Agency for Planning and Building Services in the Municipality of Bergen. Figure A0.1 shows how the area zones are divided, which set base for the demographics provided in figure ??. The prospects for the depots for the Blue Light Rail is within the three area-zones: Sandviken, Sentrum and Laksevåg.

Figure A0.1: Area zones: Bergen

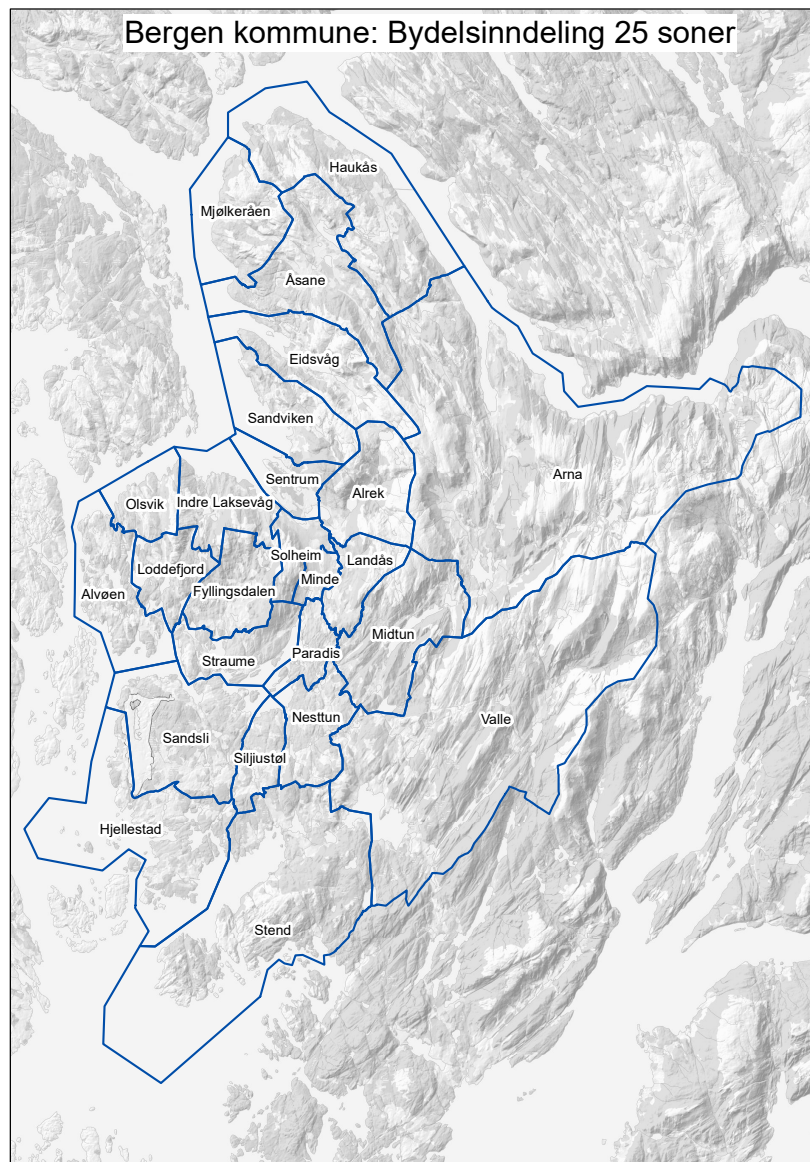
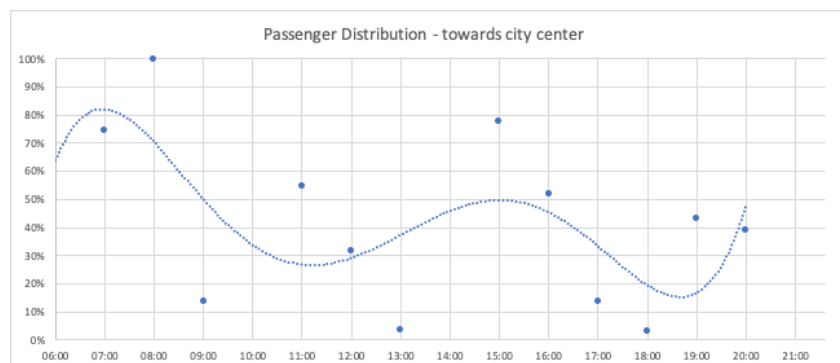


Table A0.1: Demographics: Targeted areas of Bergen

Years	0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-110	Total
Eidsvåg	1278	641	628	749	768	421	354	149	47	5035
Indre Laksevåg	3008	2825	2464	1897	1616	1125	833	434	84	14286
Sandviken	2800	3817	2419	2066	1901	1507	1119	671	165	16465
Sentrum	2547	6983	3693	2252	1762	1493	986	418	161	20295
Solheim	2018	4561	2717	1449	1130	837	441	244	60	13457
Total	11651	18827	11921	8413	7177	5383	3733	1916	517	69538

B Demand generation process

The demand generation was constructed in a process of several steps, using Excel as tool. In order to identify traveling patterns using public transportation in Bergen, counts retrieved by COWI (2015) was used. These counts was conducted on selected bus-lines in the municipally. The counts towards the city center was used for the distribution analysis. This because the demand estimates retrieved from (Onarheim et al., 2019) are based on passenger flow towards the city center. The distribution created for a day is presented in figure A0.1 below

Figure A0.1: Distribution towards city center

Some hours are excluded from the counts, which limits the validity of the distribution. Therefore, I chose to split the distribution in counted periods, and consequently a morning, noon and evening distribution was conducted. These are the distributions presented in the Data-chapter. To make use of these distributions, polynomials defining the pattern were retrieved from Excel and used to evaluate percentage flow for each 15 minutes during the respective time periods. The demand retrieved from Onarheim et al. (2019), was based on flow for an hour, being 07:00-08:00. To further split the max-hour to investigate

shorter time-period demand, I split the number into quarters. With no further information on how the flow within the max-hour was, I assumed the peak-quarter was 1/4 of the max-hour. To demonstrate the calculation, the below process shows demand at time 06:45 for passengers from Laksevåg-Nøstet.

1. Use the polynomial for the morning distribution to calculate share of max-demand at the time. $y = 495,33x^2 - 6348,5x^2 + 21420x - 15295$, such that y is the share and x is the time. For 06:45, $y = 39\%$
2. The share is used to calculate the number of passengers at the selected time, based on the max-quarter. For the expected demand, 39% equals four passengers from Laksevåg-Nøstet.
3. All being within formulas in Excel, it is an intuitive process to increase and decrease demand.

The table below represents the OD-pairs, including pickup- and delivery location, demanded time of arrival and the number of passengers per group.

Table A0.1: Representation of an OD-pair

Pass.nr	Pickup.loc	Delivery.loc	Dem.time.arr	Passengers
1	Laksevåg	Nøstet	06:30:00	3
2	Laksevåg	Nøstet	06:45:00	4
3	Laksevåg	Nøstet	07:00:00	6
4	Laksevåg	Nøstet	07:15:00	7
5	Laksevåg	Nøstet	07:30:00	7
6	Laksevåg	Nøstet	07:45:00	8
7	Laksevåg	Nøstet	08:00:00	7
8	Laksevåg	Nøstet	08:15:00	7
9	Laksevåg	Nøstet	08:30:00	6
10	Laksevåg	Nøstet	08:45:00	4
11	Laksevåg	Nøstet	09:00:00	1
...				

C Route generation process

The route generation is based on the 20 routes and the corresponding travel times between them. This appendix will provide a step-by-step process on how routes for the ferry network were conducted.

1. Nautical distances between all nodes in the ferry network were drawn and calculated using tools from Kartverket. Followingly, travel times were calculated based on speed limits and assumed speed for the ferries.
2. Using Excel, I generated formulas that recognized names and travel times for and between the respective depots. In addition, an extra 2 minutes between every connection were added, to account for e.g. acceleration and speed reduction due to speed limitations and docking. Then I plotted all the routes and set a start time.
3. Thereafter, schedules for the 20 routes were automatically generated in a common sheet, which I could use for further analysis.
4. To provide further options for route selection, three start times were used, with a 5 minute difference.

An example of a route, k10 is presented in the following table.

Table A0.1: Schedule for k10

trip.nr	node1	arr.node1	dep.node1	node2	arr.node2	dep.node2
1	NOST	06:00:00	06:00:00	LAKS	06:03:13	06:05:13
2	NOST	06:08:26	06:10:26	LAKS	06:10:26	06:12:26
3	NOST	06:15:39	06:17:39	LAKS	06:20:52	06:22:52
4	NOST	07:18:30	06:28:05	LAKS	06:31:18	06:33:18
5	NOST	07:45:20	06:38:31	LAKS	06:41:44	06:43:44
6	NOST	08:12:10	06:48:57	LAKS	06:52:10	06:54:10
7	NOST	08:39:00	06:59:23	LAKS	07:02:36	07:04:36
8	NOST	07:07:49	07:09:49	LAKS	07:13:02	07:15:02

Where "NOST" and "LAKS" is Nøstet and Laksevåg, respectively. Furthermore, all departures are two minutes later than arrivals such that the schedules account for a pickup and delivery, hence a service time.

D Column Generation

This appendix presents examples from the Column generation, to illustrate further how the approach was conducted.

First, routes and passengers were matched using R programming as tool. The model includes all constraints needed to ensure the passengers were allocated the correct routes.

As the model is formulated in Chapter 4, this Appendix will not re-describe it, but supplement with examples.

The table below shows the table matching passengers and routes.

Table A0.1: Matching Routes and Passengers

Route	Trip	Orig	Dest	OD-pair	Q.pass	Node1	Arr.1	Dep.1	Node2	...
5	6	SAN2	STRA	189	11	SAN2	08:15	08:17	STRA	
18	6	SAN2	NOST	148	12	LAKS	08:17	08:19	NOST	
16	6	SAN2	NOST	148	12	SAN2	08:14	08:16	NOST	
1	5	SAN2	STRA	190	7	SAN1	08:23	08:25	SAN2	
10	13	LAKS	NOST	7	7	NOST	08:00	08:02	SAN2	

As this is just a short example, node 3 and 4 is not included, for the case of simplicity. The table shows the OD-pairs with corresponding request (also demanded time of arrival and earliest time of arrival are considered in the model). Furthermore, as the table shows, OD-pair 148 appears twice, this is because multiple routes can fulfill the OD-pairs requirements. The size of this table depends on the set constants, if the passengers allow high patience and the routes require a low number of passengers per OD-pair (Q.pass in table), the table can include hundreds of observations.

The table is used to create a binary matrix, with routes as columns and OD-pairs as rows. 1 indicates whether a route fulfills the requirements for an OD-pair, and 0 otherwise.

Finally, the model selects the minimum combination of routes that fulfill demand for all OD-pairs.