Norwegian University of
Science and Technology

Master's thesis

2020

Ingvild Eide Aslaksen, Elisabeth Bjerke Svanberg

Master's thesis

NTNU
Norwegian University of
Science and Technology
Faculty of Economics and Management
Department of Industrial Economics and Technology
Management

Ingvild Eide Aslaksen
Elisabeth Bjerke Svanberg

A Combined Ferry Service Network Design and Dial-a-Ride System for the Kiel Fjord

June 2020

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Ingvild Eide Aslaksen
Elisabeth Bjerke Svanberg

Industrial Economics and Technology Management
Submission date: June 2020
Supervisor: Kjetil Fagerholt
Co-supervisor: Frank Meisel
Lennart Johnsen

Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management

Preface

This master's thesis is written in the spring of 2020 as a part of our Master of Science in Engineering at the Norwegian University of Science and Technology (NTNU), Department of Industrial Economics and Technology Management. It builds on a report written in late 2019 during our specialization project within the subject of Managerial Economics and Operations Research. Furthermore, the thesis is written as a part of a larger project, CAPTin Kiel, which is an ongoing initiative at Kiel University in Germany.

We give our deepest gratitude to our supervisor Prof. Dr. Kjetil Fagerholt for exceptional guidance, feedback, and encouragement. Moreover, we would like to thank our co-supervisors, Prof. Dr. Frank Meisel, and Dr. Lennart Johnsen at Kiel University for splendid collaboration, and the opportunity to be given this assignment.

Ingvild Eide Aslaksen & Elisabeth Bjerke Svanberg

Trondheim, June 2020

Abstract

The evolution of autonomous mobility solutions may change public transportation as we know it by enabling more frequent departures, shorter detours, and on-demand services. This master's thesis presents an operations research study of a ferry service design, and it contributes to a larger project at Kiel University in Germany. The aim is to develop a mathematical model and a simulation system, which may provide decision support to the implementation of a public ferry service for passenger transportation in the Kiel fjord using autonomous ferries. Furthermore, the proposed models contribute to research on public transportation network design, both considering the construction of a fixed departure schedule and the use of dial-a-ride services.

Initially, this thesis presents a integer programming optimization model regarding the design of routes for a public ferry service, including the selection of departure frequencies. The model is based on a two-step optimization approach, where candidate combinations of routes and departure frequencies are generated a priori. Afterward, the solution network is constructed with a bi-objective approach which considers maximizing departure frequency and minimizing excess transit time through customized utility functions. The route generation procedure allows more complex structures with up to two visits to all ports in the route. Moreover, as an addition to current service network design literature, the concept of minimum required frequencies specific to origin-destination pairs is introduced. This enables greater control over the available connections offered by the service network for the operator.

Subsequently, this thesis formulates the problem of combining a fixed schedule service with a demand responsive service without passenger transfers, which has scarcely been studied in previous literature. The aim is to maximize the number of serviced requests within certain quality requirements while minimizing service time. A simulation system is developed to evaluate the effects of different ferry allocations, and the aim is to provide insights into the relations between the predictability of a fixed schedule with time tables and the responsiveness of a dial-a-ride service with on-demand routing. During the simulation, each passenger request is either accepted or rejected. Accepted requests are assigned to specific ferries by applying a constructed insertion heuristic, which also considers redirection of the dial-a-ride ferries.

The proposed optimization model to create fixed schedule departures is solved to optimality within reasonable time for up to ten ports. However, due to combinatorial explosion in the route generation procedure, the scalability is poor for additional ports. Apart from this, the results indicate that the level of customer service in Kiel may be improved compared to the current ferry service offering, both considering elevated departure frequency and reduced excess transit time.

The analyses conducted of the combined ferry service system reflect that the optimal fleet allocation between the two services to a large extent depends on the size of demand. Peak hours with high demand may benefit from the predictability of the fixed schedule, whereas off-peak periods with more scattered demand is suitable for an increased dial-a-ride service, due to its flexible and responsive behavior. Moreover, the fleet size also appears to affect the choice of allocation. Fixed schedule services are preferable for smaller fleets, while a predominant dial-a-ride service provides a higher level of customer service for larger fleets. In addition, applying minimum required frequencies can improve the performance of the fixed schedule, thus further research into this concept is encouraged. In conclusion, autonomous technology advancements combined with the proposed decision support tools may provide excellent customer service for public ferry transportation systems.

Sammendrag

Utviklingen av autonom teknologi åpner for nye løsninger og kan revolusjonere dagens infrastruktur for offentlig transport ved å tilby hyppigere avganger, kortere omveier samt on-demand tjenester. Denne masteroppgaven omhandler fergenettverksdesign, og er skrevet i et operasjonsanalyseperspektiv. Oppgaven er en del av et større prosjekt på Christian-Albrechts-Universität Kiel, i Tyskland. Formålet med oppgaven er å presentere en matematisk modell og et simuleringsrammeverk, som kan gi beslutningsstøtte til implementeringen av et offentlig fergetilbud i Kielfjorden ved bruk av autonome ferger. Videre kan modellene føye seg til forskningen på offentlige transportnettverk, både når det gjelder faste timetabeller, og bruk av on-demandtjenester.

Et heltallsproblem er formulert for å designe ruter og velge deres respektive avgangsfrekvenser. Modellen er basert på en to-stegs optimeringsmetode hvor kandidatruter og deres avgangsfrekvenser konstrueres på forhånd, og deretter blir det optimale settet av ruter og frekvenser bestemt ved å løse heltallsproblemet. Målfunksjonen er formulert som et bi-objektiv hvor både maksimering av avgangsfrekvenser og minimering av reisetid for passasjerene blir tatt hensyn til. Disse to aspektene er vektet ved hjelp av en ulineær nyttefunksjon. Rutegenereringsalgoritmen genererer komplekse ruter med opptil to besøk i hver havn. Videre, som et tilskudd til litteraturen, blir det presentert en skranke på et minimum antall avgangsfrekvenser mellom hvert havnepar. Dette åpner opp for ytterligere kontroll over forbindelsene rutenettverket tilbyr.

Det er også formulert et problem som tar for seg kombinasjonen av et fast rutenettverk med en on-demandtjeneste, hvor fergene tilpasser sine ruter etter der det oppstår etterspørsel. Systemet modelleres slik at alle passasjerer kan reise uten behov for omstigning, og dette er per dags dato lite diskutert i litteraturen. Målet er å maksimere andelen av etterspørsel som kan bli møtt innenfor satte grenser av kundeservice, samtidig som total reisetid i systemet minimeres. Et simuleringsrammeverk er utviklet for å evaluere kvaliteten på systemet med ulike allokeringer av ferger på det faste nettverket og til bruk av on-demandtjenesten, og formålet er å oppnå innsikt i relasjoner mellom forutsigbarheten til et fast rutenettverk og fleksibiliteten til en on-demandtjeneste. I simuleringsrammeverket blir reiseforespørsler godtatt eller avvist, og de godtatte forespørslene allokeres enten til det faste rutenettverket eller

til en on-demandferge. For å finne en optimal behandling av etterspørselen ved hjelp av on-demandtjenesten, er en innsettingsheuristikk utviklet og implementert.

Den presenterte optimeringsmodellen for å konstruere faste rutenettverk ble løst til optimalitet innenfor rimelig tid for opptil ti havner. På grunn av en kombinatorisk eksplosjon i genereringen av ruter skalerer modellen dårlig for instanser med flere enn ti havner. Resultatene fra modellen for øvrig indikerer at kundeservicenivået i Kiel kan bli betydelig forbedret fra slik det er i dag, både med tanke på avgangsfrekvenser og reisetid.

Resultatene fra analysene gjort med simuleringsrammeverket viser at den optimale allokeringen av ferger mellom de to tjenestene som tilbys (fast rutenettverk og on-demandtjeneste) varierer med mengden etterspørsel. I rushtid med høy etterspørsel kan det være fordelaktig med forutsigbarheten og effektiviteten til det faste rutenettverket, mens i perioder med mindre, mer sporadisk etterspørsel, kan det være fordelaktig å benytte seg av fleksibiliteten til en on-demandtjeneste. Videre er det observert at flåtestørrelse har mye å si for hvordan fergene bør allokeres. Et fast rutenettverk er fordelaktig når flåten er liten, men med større flåte kan flere on-demandferger føre til bedre utnyttelse. I tillegg virker det som bruken av skranker på et minimum antall avganger mellom hvert havnepar kan øke kundeservicenivået på det faste rutenettverket slik at et supplement med on-demandferger ikke er like nødvendig. Dette er et spennende funn som det oppfordres til å forske videre på. For å konkludere, indikerer funnene fra denne masteroppgaven, at ved hjelp av de presenterte beslutningsstøtteverktøyene kan nyvinningene innen autonom teknologi for passasjertransport utnyttes for fergetjenester, slik at det stadig mer etterspurte tilbudet for offentlig transport kan tas til nye høyder.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

The World Health Organization estimates that 60% of the world's population will be living in urban areas by the year 2030 (Global Health Observatory, 2014). Large cities will continue to grow and increase the pressure on public transportation networks. Although eight out of ten of the world's largest cities are located either by the coast or a river, public ferry transportation systems are rarely utilized. However, water transit infrastructure is gaining increased interest (Wortman, 2017). Therefore, further research on public ferry service offerings may present great potential with respect to reducing congestion on urban road networks and connecting new locations. Furthermore, due to the recent advancements in digital technology, demand responsive transit solutions may now be combined with fixed schedule departures to provide passengers with outstanding customer service. With this in mind, and also considering the increasing use of autonomous transportation options, global passenger logistics may be revolutionized.

This thesis contributes to a larger project at Kiel University, named *CAPTin Kiel*, "Clean Autonomous Public Transport in Kiel". The overall aim is to provide decision support to the implementation of a ferry service offering for passenger transportation in the Kiel fjord using autonomous passenger ferries. Firstly, we present and discuss a solution method regarding the design of routes for a public ferry service network, including the selection of departure frequencies. This problem is henceforth referred to as the Ferry Service Network Design Problem (FSNDP). Secondly, we present a combined transportation system, where a fixed schedule service based on the solution of the FSNDP, is supplemented by a *dial-a-ride* service, in which ferries can be called upon and rerouted, similar to a rideshare taxi service. This system is subsequently referred to as the Combined Dial-a-Ride and Fixed Schedule for a Ferry Service (C-DAR-FS).

Even though a ferry network already exists in Kiel, we consider the shift to a system of autonomous ferries to be extensive, and therefore, we have designed a new network instead redesigning the existing. All technical and legal issues regarding the implementation of autonomous ferries are outside the scope of our thesis. Moreover, since the technology of autonomous ferries is new, the cost structures are relatively unknown, and profit optimization is challenging. Therefore, and to coincide with the vision of CAPTin Kiel, the aim of both the FSNDP and the C-DAR-FS is to maximize customer service.

The success factors of the project are connected to the passengers' perception of the ferry service quality. We consider good customer service to be short travel times and high frequency of departures, which coincides with Kiliç and Gök (2013) who state that "passengers prefer to choose the shorter paths and minimum number of transfers to get to their destination". Fang and Zimmerman (2015) also state that transfer is often perceived as troublesome for passengers. Hence, since the Kiel fjord is small with short travel distances, we argue it should be possible to design a ferry service without the need for transfer. Moreover, good customer service has traditionally been related to understandable ferry schedules, and the current ferry service in Kiel contains only two routes, which enables compact physical timetables. However, new technology is changing the way passengers travel by providing digital travel planners, e.g. apps. Thus, it enables more complex service networks, that can provide higher service quality through rapid and manifold departures.

The FSNDP is formulated as a integer programming optimization model, which provides decision support to the scheduling of a fleet of ferries to specific routes and departure frequencies. The model is based on a two-step optimization approach where candidate combinations of routes and departure frequencies are generated a priori. The generated routes allow structures with up to two visits to all ports in the route, henceforth denoted a *chain* structure. The objective of the FSNDP is twofold. Short transit times, and especially reduced detours, are deemed important for good perceived customer service. Thus, the objective of the FSNDP seeks to minimize *excess* transit time for the passengers, i.e. the extra time a passenger spends in transit compared to the time of a direct ferry. Furthermore, the ferries should depart at a high frequency, which offers the passengers a flexible service. Therefore, the objective of the FSNDP also considers the frequency of departure for the routes.

The C-DAR-FS aims to identify the optimal ferry allocation with respect to customer service for a given fleet size. A ferry allocation states the number of ferries allocated to each of the two available services; the fixed schedule (FS) and the dial-a-ride (DAR). We have developed a simulation system with a request assignment procedure to evaluate solutions of the C-DAR-FS, and by testing variations in different parameters, we gain insights into general trends of the allocation strategy. Overall, we attempt to identify relations between the predictability of the fixed schedule and the responsiveness and flexibility of the dial-a-ride service. The simulation system models the occurrence of passenger requests, and each request is assigned to either of the two services, if accepted. The request assignment procedure identifies the best feasible assignment of both service types, where an insertion heuristic is constructed for evaluation of the DAR-service. Furthermore, the request assignment procedure attempts to achieve a high level of customer service by maximizing the number of serviced requests while minimizing the average time spent in the system by all passengers.

This thesis aims to contribute new knowledge within two emerging fields of investigation. Firstly, the modeling of the FSNDP introduces *minimum required frequencies* per origin destination pair (*OD-pair*), which may ensure departures between specific locations across all services. This is contrary to the common way of assessing public transportation networks, where a minimum departure frequency is linked to a route, not an OD-pair. We argue that the passengers do not mind the route they take, as long as they are able to travel between their desired OD-pair within reasonable time. This concept is not seen in previous public transportation literature. Secondly, we formulate the problem of allocating a fleet of ferries between two service types; fixed schedule departure and dial-a-ride. The simulation system constructed to evaluate allocations, guarantees the serviced passengers to reach their destination within a certain level of quality without the need for troublesome transfers. The focus on allocation strategies between the fixed schedule departures and the dial-a-ride service is uncommon in the literature, and to the best of our knowledge, our modeling of the interaction between the two services has not yet been researched. Note that the ideas provided in this thesis may be applied to other mobility solutions, e.g. buses.

The outline of the remainder of this thesis is as follows. Relevant background material is presented in Chapter 2. Then, we begin a two-part structure of the thesis. In Part I we present the FSNDP. First, Chapter 3 presents a review of relevant literature. Then, a qualitative description of the FSNDP is presented in Chapter 4, followed by the mathematical formulation in Chapter 5. Chapter 6 describes how the combinations of routes and departure frequencies are generated a priori using heuristic rules. Test instances for the FSNDP are displayed in Chapter 7, and a computational study is conducted and presented in Chapter 8. In Part II we present the C-DAR-FS. An overview of relevant literature is provided in Chapter 9. Chapter 10 describes the modeling of the C-DAR-FS, and in Chapter 11 we present the insertion heuristic for assigning a request to the DAR-service. The computational study for the C-DAR-FS is presented in Chapter 12. Lastly, concluding remarks for the two parts in conjunction are given in Chapter 13, and Chapter 14 provides suggestions for future research.

Chapter 2

Background

In this chapter, we present some relevant background information to support the research conducted in the thesis. Firstly, the city of Kiel is briefly introduced, and secondly, the current ferry service network is presented with illustrations and operational details. Thirdly, the initiator of this thesis is introduced, which is a project named *CAPTin Kiel*. Lastly, we discuss some aspects of deploying autonomous ferries and the use of dial-a-ride services.

Kiel is a major maritime center at Germany's Baltic coastline. It has 250 000 inhabitants and is the capital of the region Schleswig-Hostein. Kiel is a seaport city, which is split by a fjord named the *Kieler Förde* or the Kiel fjord. Therefore, several cruise ships and industrial ships travel in and out of the fjord every day. An interesting characteristic of Kiel is the current infrastructure. It was to a large extent rebuilt and constructed after the Second World War. Thus, it is mainly built to accommodate car transportation on roads around the fjord, whilst the fjord has primarily been used for transportation of industrial goods.

Nevertheless, the city of Kiel has an existing ferry service offering, operated by *Schlepp- und Fährgesellschaft Kiel* (SFK), which deploys conventional, i.e. non-autonomous, ferries. The ferries are relatively large, with a capacity of 300 passengers (und Fährgesellschaft Kiel, 2010). Therefore, they seldom operate at full capacity. It is only during the "Kieler Woche", an annual sailing festival in June, that the ferries experience challenges with capacity. The SFK offers two ferry lines, displayed in Figure 2.1. Ferry line 1, the "Förde-Fährlinie", travels up and down the fjord, while Ferry line 2, the "Schwentine-Fährlinie", serves the connection between the east and west. In addition, Ferry line 1 is extended during the summer season, with three additional ports. The demand to and from the different port varies, due to e.g. the type of area surrounding the ports. "Bahnhof" and "Laboe" are examples of some of the more popular ports.

As Figure 2.1 illustrates, most port pairs do not have a direct connection. Moreover, all ports have at most one single ferry departure scheduled every hour, implying

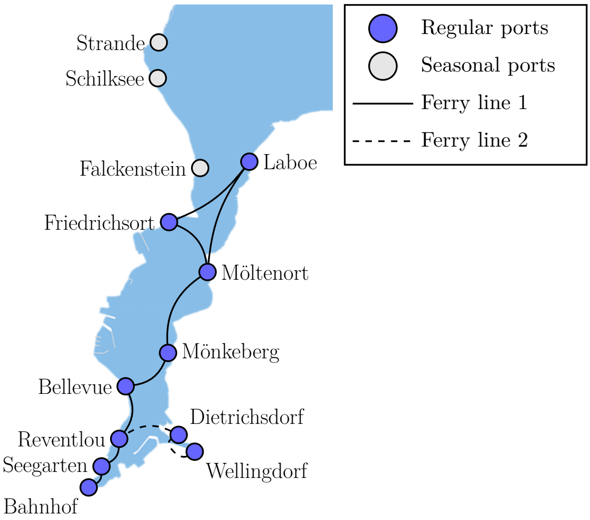


Figure 2.1: Illustration of the current ferry service offering in the Kiel fjord.

that the frequency of departures is low. Also, the route traversed by Ferry line 1 changes between departures. Due to long transit times, limited frequency of departures and changing schedules, the current ferry service is mostly used for recreational purposes, only rarely appealing to commuters. Ferry line 2 presents a slightly more direct connection across the fjord, and is therefore somewhat more used by commuters. Note that there are no car bridges connecting the locations across the fjord.

CAPTin Kiel is a collaborative project, which was initiated by Kiel University in 2017. Besides Kiel University, other academic institutions and several industrial firms are involved, as well as the local and federal government. The project is a transdisciplinary innovation platform with a goal to develop a complete and integrated public transportation system with autonomous and clean mobility solutions. The vision of CAPTin Kiel is ”an urban mobility system that is more and more characterized by autonomous solutions, which is safe, pollution-free and climate-friendly, and significantly reduces individual traffic and links the different modes of transportation on land and water in a user-friendly and intelligent way” (Pankratz and Müller-Lupp, 2020*a*). To significantly reduce individual traffic, the public transportation system must attract passengers by providing a high level of customer service.

One part of the platform covers the design and implementation of a new *ferry service* offering in Kiel, using autonomous ferries. The term ferry service encapsulates the complete offer of ferry lines, i.e. routes, as well as the possibility of on-demand solutions, which the citizens of Kiel can utilize. Even though ferries travel across the fjord today, the potential for the fjord to offer a flexible and efficient mobil-

Figure 2.2: Suggestions for the design of the new autonomous ferries (Pankratz and Müller-Lupp, 2020*b*).

ity system is far from utilized due to infrequent departures and few routes. This thesis addresses the new design by proposing a model for the creation of new schedules (the FSNDP) and by studying the effects of supplementing with a dial-a-ride service. The aim is to design a public transportation ferry service offering which delivers excellent customer service. Thus, the citizens of Kiel may choose to travel by ferry rather than private transportation.

Moreover, since the autonomous technology for the new ferries is yet to be developed, other research groups within the CAPTin Kiel project aim to solve the technical issues regarding the autonomous ferries. In collaboration with the federal government, the CAPTin Kiel project is currently planning the establishment of a test field for autonomous ships in the Kiel fjord, where testing of digital autonomous systems can be executed. Also, in collaboration with the SFK, they will test autonomous components on a 100 passenger electric ferry, which will be deployed on Ferry line 2 by 2021 (Pankratz and Müller-Lupp, 2020*b*). Furthermore, a project group at the Muthesius Academy Kiel is aiming to design the autonomous ferries, and two suggestions are illustrated in Figure 2.2.

Autonomy means that operations happen automatically, controlled by machines, and not humans (Cross and Meadow, 2017). Hence, a fully autonomous ferry could be operating on water without any captain or other crew stationed at the ferry. This facilitates new cost structures, and can enable the use of several smaller ferries, thus providing a more flexible and rapid ferry service offering. The technology, documentation and regulations needed for autonomous transportation are yet to some extent undeveloped (Gu et al., 2019). However, the interest for the technology is high, and in 2018, Rolls-Royce and Finferries conducted a demonstration of the world's first fully autonomous ferry with 80 passengers on board. Mikael Makinen, Rolls-Royce President – Commercial Marine, claims that "the demonstration proves that the autonomous ship is not just a concept, but something that will transform shipping as we know it" (Rolls-Royce, 2018).

On a final note for the background material, utilizing dial-a-ride services for urban transportation was already recommended in the sixties (Cole, 1968), but the technology has not enabled real-time large-scale operations until recently. For the last decades, the dial-a-ride service has been an important service for the elderly or disabled who cannot make use of regular public transportation. Thus, this service has mostly been seen as a last-mile offer for special users in connection with fixed schedule departures, or as a separate service as an alternative to other transportation methods. However, the interest for various rideshare mobility options is increasing due to urban congestion and pollution, and technological advancements, e.g. digital apps, have enabled a potential for demand responsive transit (Association and of Mechanical Engineers, 2017). Therefore, the dial-a-ride service is now being explored to a greater extent as a large-scale transportation method for regular passengers as well, both as a stand-alone service and as a supplement to fixed schedule departures.

Part I

The Ferry Service Network Design Problem

Chapter 3

Literature Review I

In this chapter, a study of relevant literature for the FSNDP is presented. Firstly, in Section 3.1, we present a general review of network design problems (NDP). Secondly, in Section 3.2, we review ferry network design problems (FNDP) specifically.

3.1 General Review of Network Design Problems

The Ferry Service Network Design Problem (FSNDP) addressed in this thesis is a type of network design problem (NDP). It shares properties with optimization problems regarding both public transportation and maritime optimization, particularly liner shipping. The network design problems inherent to public transportation (PTND) and liner shipping (LSND) have been thoroughly reviewed by Svanberg and Aslaksen (2019). They used ”Scopus” as search engine, and the detailed search procedure can be viewed in Appendix A. In the following section, we provide a summary of the most important findings from that review.

Network design problems may have different objective functions, and we proceed to sum up some of the most common. On the one hand, the LSND problems tend to optimize a monetary value, either a cost or a profit, where operational costs often are included, such as fuel costs, port call fees or an overall operating cost which encapsulates all costs. Example papers include Brouer et al. (2014) and Thun et al. (2017). On the other hand, the most common objective in public transportation network design is to minimize overall cost, which considers both *user cost* and *operator cost* ((Martínez et al., 2017) and (Wang and Lo, 2008)). Regarding user cost, *customer service* is often a topic of interest. Short waiting time, no or seamless transfer, no walking, enough information, and in general an integrated transportation system are important for the perception of good customer service (Fang and Zimmerman, 2015). Thus, user cost is often interpreted as time, both waiting time and transit time, but it can also include other inconvenience factors such as transferring, waiting in hostile areas, lack of information and so on.

Operator cost could be a variable cost per ride, e.g. fuel consumption, or fixed cost, which is often simplified to procurement of transportation vessels (Baaj and Mahmassani, 1995).

In a seminal paper, Ceder and Wilson (1986), were among the first to present an objective, combining operator and user costs. They did this by minimizing *excess* transit time, i.e. the difference between the actual and the shortest available transit time. Their model allows passengers to travel on multiple paths, thus enabling different bus routes to serve the same OD-pair. The formulation comprises a minimum frequency of departures per route, which ensures a route cannot be selected unless it is offered a certain amount of times. Moreover, they present a route construction algorithm to find the shortest path for all OD-pairs, and other feasible routes which does not differ too much from the shortest path.

In a more recent publication, Suman and Bolia (2019) seek to maximize directness, which, according to their definition, is given as the total *passenger-kilometers* (PKM) traveled in the system, without any transfers. They formulate a linear model that enables an exact solution with no need for heuristics. The model seeks to redesign an existing network through route improvement, where the origin and destination of the route are already defined. Thus, the aim is to alter the visiting sequence of stops between the start and end point of the given routes. The feasible alterations (paths) are limited by a maximum allowed detour length, but since they disregard the capacity of the buses, the solution space is relaxed. They also briefly discuss an important aspect, where they argue that passengers do not mind the route they take to get to their destination.

The LSND models often impose a fixed weekly (or bi-weekly) frequency requirement for all OD-pairs, where similar ships are deployed to the same route to fulfill this fixed frequency (Brouer et al., 2017). Moreover, the round trip duration for a route is often constructed to be a multiple of a week to simplify the assignment of ships. However, Giovannini and Psaraftis (2019) discuss the effects of allowing flexible service frequencies at the tactical level of planning. Here, the routes are considered as given, and the aim is to determine the required service frequency, sailing speed and number of ships deployed that maximizes the profits. They find that ”the cost of forcing a fixed (weekly) frequency can sometimes be significant”, and therefore, they argue that a worthy extension to their model would incorporate the flexible service frequency with other stages of planning, e.g. network design and fleet mix. As briefly discussed, PTND problems often decide and restrict the frequency of departure for routes, but not for OD-pairs. Therefore, to the best of our knowledge, to date, neither LSND, nor PTND problems have been solved using different minimum frequency requirements per OD-pair. This thesis and the proposed model to the FSNDP aim to contribute to this area.

In addition, route structures are of importance when solving network design problems. Regarding route structures, the FSNDP shares important properties with LSND problems, because it concerns the design of a network of cyclic routes on sea, which is published in a fixed service schedule. Since non-maritime PTND problems often involve bus or rail as transportation mode, the routes must follow given corridors (e.g. roads), so they usually exploit single-visit sequences, which is repeated back and forth ((Ceder and Wilson, 1986), (Schmid, 2014), and (Martínez et al., 2017)). LSND problems usually allow more complex routes, which imply a more comprehensive model and route generation procedure. Traditionally, LSND modelled simple routes, often with an inbound and outbound structure, but the more recent literature aims at designing more complex and sophisticated route structures. Brouer et al. (2014) present a selection of route structures, including line bundled, butterfly and chain routes (also sometimes denoted conveyor belt routes). Thun et al. (2017) reformulate the LSND model to account for more complex route structures without limitations on the number of visits to each port, and they solve it using a branch-and-price method for route structures with up to two visits per port. This enables the construction of e.g. chain route structures. The FSNDP will exploit the chain structure when generating routes, as this provides suitable route structures for a narrow fjord.

Moreover, there are various ways of constructing routes and solving network design problems. Brouer et al. (2014) define a *rotation* as a specific configuration of a route, ship type, number of ships deployed and speed. Thun et al. (2017) present the similar concept without speed, and denote it a *service*. They divide the LSND problem into a master problem and a subproblem, where the master problem coordinates the services and the transshipments, while the subproblem generates new services, along with a set of different possible delivery patterns for that specific service. However, the frequency of the service is fixed at a week, so the master problem does not consider the time dimension as it coordinates the services. The only time considered is a maximum duration of service, which limits the round trip time. Therefore, their presented model allows complex route structures, but does not consider transit time of the cargo through the network. Plum et al. (2014) also present a model that allows multiple port calls to a port within a service. They construct the services by arc decision variables, and then the cargo is transported through the network either on a single service or on a combination of several services, thus allowing transshipment. Specialized service-port arcs are introduced to handle the multiple calls, which prevent "cheating on capacity" in the network. However, due to the large number of variables and constraints, they were unable to solve their test instances to optimality. In an interesting approach, Brouer et al. (2017) divided algorithms for solving LSND problems into four categories depending on the connection between the vessel route design and the cargo flow:

- *Integrated approaches* which solve small instances of vessel route design and container flow simultaneously.

- *Route-first-flow-next approaches* which apply a two-step analysis that generates vessel routes first, then distributes the containers. It may require several iterations between route generation and distribution of containers before the optimal solution is identified.

- *Flow-first-route-next approaches* which also apply a two-step analysis, but first flow containers through the network and afterwards construct the routes.

- *Selection of routes* which assumes a set of feasible vessel routes are generated manually or by constructive algorithms, and then chooses the most appropriate for the network. This implies that all feasible routes are generated a priori, and the problem is simplified to finding the best combination of these routes.

The last category is the most interesting for the FSNDP, because feasible route and frequency combinations (similar to a simple rotation or service) will be generated a priori.

The literature of designing transportation networks comprises modeling approaches with both linear and non-linear models. The problems are usually very complex, because the route design and fleet deployment are considered simultaneously, which may impose non-linearities. Giovannini and Psaraftis (2019) performed a linearization to allow the use of simple tools to solve the problem as a whole, whereas Wang and Lo (2008) relaxed the non-linear constraints and solved several smaller mixed integer programs independently. Due to the complexity and the size of the problems usually addressed both in LSND and PTND, heuristic solution approaches are often developed. Wang and Meng (2014) develop a column generation based heuristic, while Karsten et al. (2017) present a matheuristic with a simulated annealing process. Martínez et al. (2017) construct a genetic algorithm to solve their model. The FSNDP shares many properties with both LSND and PTND, so it may also encounter challenges with complexity.

With this in mind, we emphasize that most of the NDP literature considers the capacity of the vessels, which adds to the complexity. However, a few articles design the network without considering the capacity, because they aim to decide the capacity at a later stage. Examples include Martínez et al. (2017), Giovannini and Psaraftis (2019) and Suman and Bolia (2019). Moreover, we observe a trend with respect to the considered fleet. Most of the PTND formulations consider a homogeneous fleet, as seen in e.g. Ceder and Wilson (1986), Schmid (2014) and Martínez et al. (2017), while the LSND literature concerns heterogeneous vessels ((Brouer et al., 2014) and (Thun et al., 2017)), which also adds to the complexity. The different trends relate to the nature of the vessels in the two problems, and the FSNDP could be modeled both with a homogeneous and with a heterogeneous fleet. The proposed FSNDP model presents a more holistic view of the network design problem, and therefore does not consider the capacity of the vessels. When disregarding capacity, a homogeneous fleet is a natural choice for the FSNDP. In conclusion, the aim of the FSNDP is to construct a simple model, which can be solved exact, while obtaining high quality solutions.

3.2 Review of Ferry Network Design Problems

In this section, we review the network design literature which includes passenger ferries as transportation mode.

The material collection for the review of the ferry network design problem (FNDP) literature was conducted using ”Scopus” as the search engine. The search was initialized by defining a relevant search string. We defined four groups of relevant keywords. All combinations of one word from each group are used as the search string, implying that the search criteria ”OR” is inserted between each word within a keyword group, and that the search criteria ”AND” is used between the groups. Firstly, we searched for articles discussing ferry as transportation mode, and hence the first keyword group simply comprises the word ”ferry”. Furthermore, we introduced a group comprising ”network”, ”route/routes/routing”, and ”schedule/scheduling” to steer the search in the direction of network of routes. The next included group comprises ”design”, ”optimization”, and ”generate/generating” in order to search for operations research articles. The last group aimed to steer the search even more towards relevant literature for the FSNDP, and therefore, this group contains the search words ”transport”, ”transit”, ”service”, and ”passenger”. We narrowed the search to only contain English articles published in journals, and we disregarded articles from irrelevant study fields such as medicine, chemistry, and environmental studies. This yielded 107 articles. After a filtration based on titles and abstract of the 107 papers, disregarding articles which do not consider operations research or irrelevant articles in terms of type of problem, we were left with 14 articles. The 14 papers were studied, and the most relevant ones are discussed in the following.

In a world with increasing need for public transportation, the interest in maritime transportation of passengers rises. However, the ferry service in large cities is often poor. Ceder (2006) approaches this by presenting an evaluation framework to assess a current ferry offering. The framework considers both existing and new routes (with new vessels and ports) as input, and thereby provides network improvement suggestions. The new route suggestions are based on the route design algorithms developed by Israeli and Ceder (1996) and Ceder (2002). The assessment considers the preferences of passengers, the operator, and the government. To assess the ferry service quality regarding customer service, they conduct a comprehensive survey and construct a detailed customer preference scheme. This provides interesting insights in how to model a ferry service that maximizes customer service.

Lai and Lo (2004) presented a mathematical model for the ferry network design problem. They formulated a tactical problem to optimize the fleet size, routing and scheduling of a ferry service. They modeled a multi-objective, where they seek to minimize operator cost in terms of the fleet size, trip operating cost and inverse revenue, and user cost expressed as the waiting time and a penalty for multi-stops. In order to track time, they represent the network as a time-space network in which each node is a given port at a given time increment. Wang and Lo (2008) present an extension of the work by Lai and Lo (2004) by introducing a heterogeneous fleet as well as heterogeneous customer preferences, making the problem non-linear. Lo et al. (2013) introduce stochastic demand to the FNDP, and they formulate a two-stage stochastic model. First, they determine routes to cover a given percent of the expected demand, and then, in the second stage, when the actual demand is revealed, they model an ad-hoc service to cover the remaining demand. An and Lo (2014) further extended this by adding user equilibrium. Moreover, Ng and Lo (2016) formulate a robust modelling of the service network design problem, and conduct a case study based on the case studies in Lai and Lo (2004) and Wang and Lo (2008). They assume that only an upper bound and the mean of the passenger demand is known. The case study showed that using ”loose information” in the absence of more exact values could lead to higher cost, which motivates more effort in obtaining accurate demand data when designing passenger transit routes.

In general, we see a trend of modeling with hard capacity constraints, and either a hard constraint on meeting all demand or a penalty for not meeting demand. This generates a number of load variables, and it also requires high quality demand estimates in order to provide valuable insights. Bell et al. (2020) present a strategic network design problem, where they disregard frequencies and ferry capacity. This simplifies the FNDP and makes it possible to identify optimal hub locations, which has been considered fixed in earlier literature. They present a method to find the maximum passenger utility spanning tree that connects all ports. The decisions in the problem are which pairs of ferry stations should be directly connected and where the ferry hubs should be located. The objective is to maximize passenger utility (minimize some function of transit time). They use the entropy maximization (EM) method to create a logit choice model which in turn generates a random utility interpretation, and they then optimize based on an expected passenger utility. However, regardless of the simplification, they do not solve the model exact, and present two heuristic approaches to solve an EM FNDP instance with 36 ports.

The FNDPs are mostly modeled with the assumption that it is possible to have direct connections between all port. This differs from traditional PTND problems, but it is very relevant for the modeling of the FSNDP. Moreover, transfer is rarely allowed, as this is often deemed unsuitable for ferry transportation (Wang and Lo, 2008). In order to model demand, both deterministic and stochastic methods are used, and sometimes an equilibrium is found using the logit model. Moreover, public transportation problems generally considers three main stake holders; the passengers, operators and local authorities ((Kiliç and Gök, 2013) and (Ceder, 2006)). These stakeholders have inherently different interests, but for the FNDP, the interest of the operator in general aligns with those of the ferry users (Bell et al., 2020). With this in mind, a natural simplification of the FSNDP considered in this thesis is to only consider the interests of the passengers, but ensuring a certain budget is kept by a constraint. Moreover, NDP problems are in general NP-hard (Baaj and Mahmassani, 1991), and the FNDPs are no exception. The problems are complex, and even with simplifications, heuristic solution methods appear to be the most common. We aim to find the sweet spot between tactical and strategic planning. Taking it a step further than Bell et al. (2020), we identify specific routes and frequencies, but still disregard ferry capacity and do not model exact load. Thereby, we keep the model simple enough to be solved exact.

Chapter 4

Problem Description I

In this chapter, the FSNDP is described in further detail. An overall ferry service network is to be determined, including the generation and selection of routes, along with their corresponding departure frequencies. The FSNDP considers a homogeneous fleet of autonomous ferries, where the size of the fleet is the only attribute of interest. Furthermore, the ferries repeat an assigned route, and in this thesis, the route is a cyclic sequence of port visits. An example of a route is illustrated in Figure 4.1. Since the routes may have more complex structures, the ferry may visit the same port more than once during a round trip. We denote different visits to the same ports as different *port calls*. Consider a route [A, B, C, B, A]. Here we denote the second entry as the first port call to port B, and the fourth entry as the second port call to port B.

The ferry service network is a part of a public transportation offering, hence the aim is to create a network with excellent customer service through optimal ferry utilization of a given fleet. Perceived customer service could be affected by e.g. how often the ferries depart, i.e. *departure frequency*, and *transit times*, i.e. the time it takes for a passenger to travel in the ferry network. Passenger demand exists between each pair of ports in the network, and the FSNDP aims to offer a service without the use of transfer. Therefore, to avoid excessively long detours, a maximum *excess transit time* is imposed on the definition of *serving* a port pair, and it compares the actual transit time with the shortest transit time available, i.e. by the use of the direct connection.

The FSNDP has a multi-objective approach balancing rapid departure frequencies and short transit times. Customer service is represented by a constructed *user utility* for each combination of a route and a frequency, which we will denote an *rf-combination*. The utility considers departure frequencies and excess transit time, weighted by expected demand to prioritize OD-pairs with high demand. Figure 4.2 illustrates a simple example where the passenger desires to travel from port A to C. On a ferry line with a direct route the transit time is 10 minutes, whilst on a route

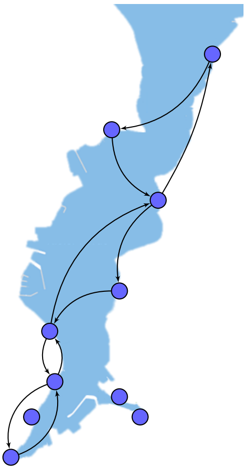


Figure 4.1: Example of a route.

where the passenger travel via port B, the transit time is 17 minutes, and hence the excess transit time is seven minutes. The objective aims to minimize excess transit time, while maximize departure frequencies to achieve good customer service.

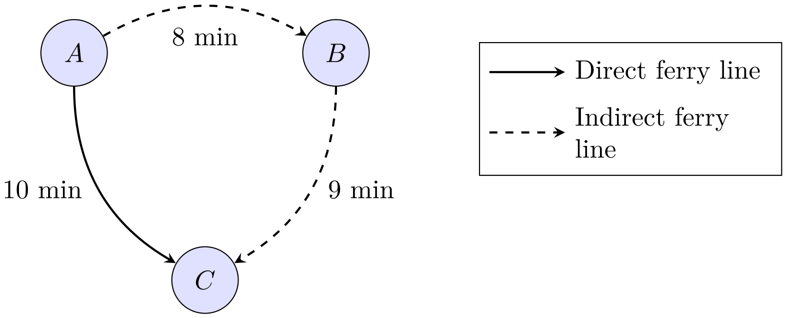


Figure 4.2: Illustration of the different transit times between a direct and indirect ferry line.

In addition, the FSNDP introduces *minimum required frequencies* specific to each OD-pair to ensure a certain service level in the network. These minimum frequencies guarantee that a ferry travels between selected ports at least a certain number of times per hour, regardless of which route it is assigned to. For instance, it could ensure that port A has a ferry service traveling to port B at least every half hour, albeit not necessarily directly. Note that since this requirement is not specific to a single route, several routes can be combined to cover the minimum requirement. Thus, the minimum frequencies are not specified for routes, contrary to most public transportation literature. The maximum excess transit times also apply to the

Table 4.1: Illustrative departure schedule with ferry waiting times.

Time	Departing Ferry	Arriving Ferry	Waiting Time in A
:00	Ferry 1	-	-
:05	-	Ferry 2	10 min
:15	Ferry 2	-	-
:20	-	Ferry 1	10 min
:30	Ferry 1	-	-
:35	-	Ferry 2	10 min
:45	Ferry 2	-	-
:50	-	Ferry 1	10 min

minimum required frequencies when assessing whether a route qualifies to ”serve” the OD-pair. The introduction of minimum required frequencies enable the operator to ensure certain departures due to e.g. political aspects, even though they may not be optimal with respect to the objective.

Moreover, to allow a restriction of the schedule complexity, we impose a maximum number of unique routes comprised in the network. This is inspired by the model extension in Svanberg and Aslaksen (2019). Thus, the operator may regulate the complexity according to his/her preference.

Lastly, we present the concept of waiting times between scheduled departures. Every route has a round trip time, i.e. the time required for the ferry to traverse the route once. In order to satisfy the chosen departure frequency, the ferry may be required to wait in a port, such that the departures from the ports are at the same time every hour. It is to be determined where, in each route, the waiting time will incur, i.e. in which port, and at which port call. The chosen port is the *waiting port*.

Extra transit time will incur for passengers if they traverse a connection of the route with an intermediate stop in the chosen waiting port at the port call where the waiting time occurs. To illustrate the concept of waiting time, take for instance the combination with route [A, B, C, A], frequency of four and a total transit time of 20 minutes. We let port A be the waiting port. The required number of ferries to operate this combination is two, as shown in Equation 4.1.

$$\lceil 4 \, \frac{1}{hour} \cdot \frac{1}{3} \, hour \rceil = \lceil \frac{4}{3} \rceil = 2 \, ferries \tag{4.1}$$

However, these two ferries will have to wait in port A between round trips, because they must follow a departure schedule. A representation of a schedule and the corresponding ferry activity is shown in Table 4.1. The scheduled departure times are marked in the first column (*Time*) in bold font. The second column (*Departing Ferry*) displays which ferry serves the given departure, while the third column (*Arriving Ferry*) states which ferry arrives at the specified time. The waiting time in port A for the ferry is shown in the fourth column (*Waiting Time in A*). As displayed in the table, the assigned ferries wait ten minutes every time a round trip is completed. Thus, passengers traveling from C to B via A will have ten minutes added to their transit time.

Chapter 5

Mathematical Formulation

In this chapter, the mathematical formulation of the FSNDP is presented. Section 5.1 presents the underlying model assumptions, before the mathematical program is presented in Section 5.2. Lastly, we elaborate on the concept of waiting ports in Section 5.3, along with the procedure for determining the waiting port for the rf-combinations.

As discussed in Chapter 4, the optimization problem should be solved and culminate in a ferry schedule that yields good customer service. The model selects a combination of routes and frequencies to maximize the sum of user utility for each route- and frequency combination. The set of rf-combinations is predefined and sent in as input in the optimization model. The generation of this set is described in Chapter 6.

5.1 Model Assumptions

This section presents the underlying assumptions in the mathematical formulation of the FSNDP. The assumptions are stated and elaborated below:

- **The routes are cyclic.** The routes of the ferry service are cyclic, i.e. they start and end in the same port. These routes are continuously repeated, and the ferries always travel their assigned route.
- **Ferry capacities are disregarded.** The route network is designed holistically, hence without modeling ferry specific passenger flow.
- **Transfers are disregarded.** The problem addresses passengers that desire to travel from one port to another. It is assumed they can only board a single ferry, thereby removing the option of transferring between ferries, i.e. the problem excludes the possibility of a hub structure. Moreover, it is assumed that passengers associate transferring with too long and cumbersome journeys, thus, ignoring transfers improves service offering.

- **The triangle inequality is satisfied for all transit times.** This implies that transit times will always be higher for indirect routes than direct.
- **Deterministic conditions are considered.** We are aware that uncertainties exist in several aspects of the problem. The input parameters used in the model are not known with certainty. However, we assume them to be known. Moreover, we assume constant transit times, i.e the transit times are not influenced by e.g. weather conditions, although they probably would vary in reality. As stochastic conditions usually add substantially to the complexity of the problem (Plum et al., 2014), we assume these deterministic conditions for simplification.

5.2 Mathematical Model

In this section, the mathematical model is presented. First the notation is defined, and then the objective function and the constraints are stated.

5.2.1 Notation

Indices:

r	Route
i, j	Port
f	Departure frequency, per hour

Sets:

$\mathcal{R}$	Set of routes
$\mathcal{P}$	Set of ports
$\mathcal{F}_r$	Set of available departure frequencies for route r

Parameters:

A_{rfij}	Number of times route r with frequency f serves the port pair (i, j) considering all port calls during one round trip
V	Number of ferries available

F_{ij}	Minimum frequency of departures from port i to j, per hour
U_{rf}	Utility associated with deploying route r with departure frequency f
R^{Max}	Maximum number of unique routes allowed
T_r	Total transit time for completing a round trip of route r
T_{rf}^{Wait}	Waiting time between round trips for a ferry on route r with departure frequency f

Decision variables:

$$x_{rf} = \begin{cases} 1, & \text{if route } r \text{ is served with frequency } f \\ 0, & \text{otherwise} \end{cases}$$

Parameter A_{rfij} is introduced to quantify how many times an rf-combination serves an OD-pair during a round trip. Even though an rf-combination contains a given OD-pair, the quality of service may be insufficient for a connection between the ports to qualify as a feasible connection, which this parameter aims to control. What defines a feasible connection is defined by attributes chosen by the operator, and we will later propose a limit on the excess transit time. We define matrix $\mathbf{A}$ as the set of A_{rfij}.

5.2.2 Objective Function

$$\max \text{ z} = \sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} U_{rf}\, x_{rf} \tag{5.1}$$

The objective in (5.1) selects the rf-combinations that maximize user utility in the ferry service network.

The utility parameter, U_{rf}, is a constructed representation of user utility in the network. The FSNDP aims to represent the trade-off between decreased transit time and increased departure frequency, thus the total user utility can be modeled as a weighted sum of utility with respect to departure frequency, U_f^F, and to excess transit time, U_{rfij}^T. Let D_{ij} be the expected demand between port i and j. It is used in combination with the number of times the *rf*-combination serves the port pair, A_{rfij}, to weigh U_f^F and U_{rfij}^T, such that sought-after OD-pairs have more impact in the objective. Hence, we define the user utility as stated in Equation 5.2.

$$U_{rf} = \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} A_{rfij}(U_f^F + U_{rfij}^T) D_{ij} \tag{5.2}$$

5.2.3 Constraints

$$\text{s.t.} \sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} A_{rfij}\, f\, x_{rf} \geq F_{ij}, \qquad (i, j) \in \mathcal{P} \tag{5.3}$$

$$\sum_{f \in \mathcal{F}_r} x_{rf} \leq 1, \qquad r \in \mathcal{R} \tag{5.4}$$

$$\sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} (T_r + T_{rf}^{Wait}) f\, x_{rf} \leq V \tag{5.5}$$

$$\sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} x_{rf} \leq R^{Max} \tag{5.6}$$

$$x_{rf} \in \{0, 1\} \qquad r \in \mathcal{R}, f \in \mathcal{F}_r \tag{5.7}$$

$$\tag{5.8}$$

Constraints (5.3) ensure every port-pair (i, j) is visited at least as often as the minimum required frequency for that given port pair. Constraints (5.4) ensure only one departure frequency is chosen per route r. Moreover, Constraint (5.5) ensures that the total number of required ferries does not exceed the number of ferries available. Constraint (5.6) limits the number of unique routes in the network. Lastly, Constraints (5.7) define the feasible area for the decision variables.

5.3 Determination of Waiting Ports

The waiting times presented in Chapter 4 are calculated by the general algorithm displayed in Equation 5.9. Here, the notation from Section 5.2 is used, and the transit time of the route is calculated with respect to the direct transit times and the berthing time of the ferry for each port visit.

$$T_{rf}^{Wait} = \frac{\lceil f\, T_r \rceil - f\, T_r}{f} \tag{5.9}$$

To illustrate the general algorithm, Equation 5.10 computes the waiting time of the ferry in the small example presented in Table 4.1. Departures are denoted *dep*, and round trips are abbreviated *rt*.

$$\frac{\lceil 4\frac{dep}{h}\cdot\frac{1}{3}\frac{h}{rt}\rceil - 4\frac{dep}{h}\cdot\frac{1}{3}\frac{h}{rt}}{4\frac{dep}{h}} = \frac{1}{6}\frac{h}{rt} = 10\frac{min}{rt} \tag{5.10}$$

The waiting time in a route will affect the passengers if they traverse a part of the route where waiting time is imposed. We choose to model the problem such that the allocation of waiting time for each *rf*-combination is chosen a priori. Another approach could be to decide the waiting ports in the optimization problem. However, we argue that deciding the waiting ports beforehand should not affect the solution quality to a great extent. When we choose to preprocess the choice of waiting ports, the size of the optimization problem becomes smaller, and hence computational time can be reduced.

To decide where to allocate the waiting time between departures for each *rf*-combination, a simple LP-problem is formulated. We use the indices, sets, and parameters from the mathematical model in Section 5.2, and introduce some additional sets and parameters, along with one new index:

Index:

k	Port and port call where waiting time is incurred

Sets:

$\mathcal{P}_r^{\mathcal{W}}$	Set of possible waiting ports and port calls in route r

Parameters:

U_{rfk}^{K}	Utility associated with the combination of route r and frequency f when waiting time is incurred in port and port call k

Decision variables:

w_{rfk}	Amount of waiting time allocated in port and port call k in route r with frequency f

We want to determine w_{rfk}, i.e allocate the waiting time, to maximize the utility such that:

For each $r \in \mathcal{R}$ and $f \in \mathcal{F}_r$:

$$\max z_{rf} = \sum_{k \in \mathcal{P}_r^{\mathcal{W}}} U_{rfk}^{K} w_{rfk} \tag{5.11}$$

$$\text{s.t.} \sum_{k \in \mathcal{P}_r^{\mathcal{W}}} w_{rfk} = T_{rf}^{Wait} \tag{5.12}$$

$$w_{rfk} \geq 0, \qquad k \in \mathcal{P}_r^{\mathcal{W}} \tag{5.13}$$

Similar to the utility presented in Subsection 5.2.2, U_{rfk}^{K} represents a trade-off between high departure frequencies and low excess transit times weighted by demand. U_{rfk}^{K} is formalized in Equation 5.14, where U_f^F is the same as stated in Equation 5.2, and U_{rfijk}^{T} is the utility related to the excess transit time from port i to port j in route r with departure frequency f and waiting port and port call k. A_{rfijk} is the number of times route r with frequency f and waiting port and port call k serves the port pair (i, j).

$$U_{rfk}^{K} = \sum_{i \in \mathcal{P}} \sum_{j \in \mathcal{P}} A_{rfijk}(U_f^F + U_{rfijk}^{T}) D_{ij} \tag{5.14}$$

However, since the LP-model only has one constraint and no upper bounds on the variables, we know it will allocate all waiting time (all of T_{rf}^{Wait}) in one port and port call of the route, i.e. only one w_{rfk} will be nonzero. Therefore, we can easily calculate which port and port call will be assigned the waiting time by choosing the k which returns the maximum value of U_{rfk}^{K} for each rf-combination. Hence, we will not solve the LP-problem directly, but instead we perform a preprocessing procedure of the input parameters. The preprocessing procedure is described mathematically as follows:

$$U_{rf} = max_{k \in \mathcal{P}_r^{\mathcal{W}}} \{U_{rfk}^{K}\} \tag{5.15}$$

After deciding the waiting ports and port calls, i.e. k^* for all rf-combinations, the values of A_{rfij} from Section 5.2 are based on the determined waiting ports and port calls, i.e. $A_{rfij} = A_{rfijk^*}$.

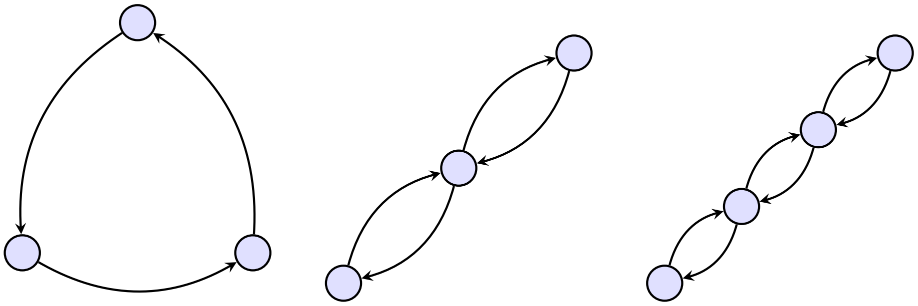
Chapter 6

Generation of Route- and Frequency Combinations

In this chapter, we present how we generate the set of candidate routes and frequencies, i.e. *rf*-combinations. First, in Section 6.1, we give a brief introduction to different route structures, and specify which structures will be included in the remainder of the thesis. Next, in Section 6.2, we elaborate on the generation procedure used to construct candidate *rf*-combinations. This includes heuristic rules used to remove undesired combinations, and the specific algorithm applied to generate these combinations.

6.1 Route Structures

Routes may have different characteristics depending on the number of included port calls in the design, and thus we continue with a brief introduction to common route structures. *Simple cycles* only allow a single port call to each of the ports included in the route, whereas *butterfly routes* enable a single port in the route, the *butterfly port*, to have at most two port calls (Reinhardt and Pisinger, 2012). If the butterfly port can have more than two port calls, the route can be described as a *flower*. In this thesis we will design routes with at most two port calls per port, i.e. all ports are treated as butterfly ports, thus enabling more complex route structures. Based on Thun et al. (2017), we denote this route structure a *chain*. Figure 6.1 displays three route structures; a simple cycle, a butterfly route, and a chain. The chain structure is practical for routes along a coast line, because the vessel may visit all ports along the coast in both directions of the route. Note that simple cycles and butterfly routes are simple versions of chain routes, and therefore they can be included as candidate routes.



(a) Simple cycle. **(b)** Butterfly route. **(c)** Chain route.

Figure 6.1: Illustration of three route structures: simple cycle, butterfly and chain.

6.2 Generation Procedure

In this section, we present the generation procedure for the set of candidate *rf*-combinations used for the FSNDP. Subsection 6.2.1 describes some rules used to define the set feasible *rf*-combinations, and Subsection 6.2.2 elaborates on the algorithm implemented to construct these.

6.2.1 Rules to Design Candidate Routes and Frequencies

We impose rules for the candidate routes and frequencies to limit the number of combinations with respect to undesirable attributes. First, we present the rules specific to the route generation procedure, and then we present a rule for the combination of routes and frequencies.

Route Rules

One way to generate the candidate routes is to combine the ports in all possible sequences for all route lengths. However, the generation would experience a combinatorial explosion. If the port is included in the route, it could be visited once or twice due to the candidate route structures, and thus, the set of ports is effectively doubled in size, $P^* = P_{1st\,call} \cup P_{2nd\,call}$. Generating all possible sequences would imply the construction of a very large set of routes, because the order of magnitude would approximately be the permutations of all ports of lengths from two to the total number of ports including two port calls, i.e. $\sum_{i=2}^{|\mathcal{P}^*|} \frac{|\mathcal{P}^*|!}{(|\mathcal{P}^*|-i)!}$ routes. Thus, the number of routes increase exponentially with the number of ports, which implies instances comprising many ports could be challenging to solve to optimality.

We seek to generate as few routes as possible to limit the complexity of the FSNDP, while ensuring good candidate routes remain included. Therefore, we develop a set of route generation rules, which aims to identify candidate routes that are deemed reasonable with respect to passenger transportation. The rules evaluate each route independently, and the set of rules are as follows:

Rule 1 Do not generate identical route cycles.

Rule 2 Include only one directional direct link per port pair in the route.

Rule 3 Routes must contain at least one ”large” port.

Rule 4 ”Adjoining pairs” must be visited consecutively.

Rule 5 Disallow north/south ”zigzagging” in the routes.

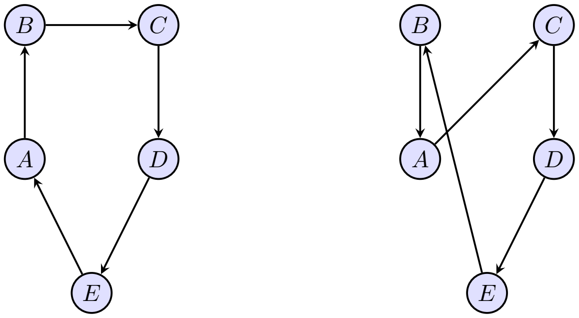
The first rule limits the number of candidate routes significantly, because we only include a single route with the same ports and visiting sequence. We choose one of the ports in the route to be the theoretical start of the route. This implies that a route with the same ports and visiting sequence, but with a different theoretical starting port, will not be included. For example, if we have routes $[A, B, C, A]$, $[B, C, A, B]$ and $[C, A, B, C]$, and port A is chosen as the theoretical starting port, only route $[A, B, C, A]$ will be included. Note that the waiting time between departures affects the route characteristics. We let the waiting port be independent of the theoretical starting port, thus, we do not remove any resulting ferry lines in this step. We will later determine which port and port call in the route that will incur the waiting time between departures, as described in Section 5.3.

The second rule restricts the number of direct connections between a port pair in a route. Candidate routes contain only a single direct connection between each port pair, thus disallowing e.g. $[A, B, C, A, B, A]$. This presents a benefit with respect to reducing the number of candidate routes. In addition, it can be argued that it is sensible to construct routes with limited subtours.

Next, the third rule aims to eliminate routes with low demand. We assume the ports have several attributes, one being a size, which should reflect the size of their demand. The demand prediction is based on what kind of area the port is located in, e.g. an industrial area, a residential area or a rather desolate area. Rule three states that all routes must contain at least one port which is defined as ”large”. We formulate this rule, because we deem it reasonable to exclude routes which only serve ports with few passengers, given that we plan the network with a limited fleet size.

Moreover, the fourth rule aims to avoid strange detours for ports located close to each other. We have defined some of the ports to be *adjoining pairs*, where the route is required to visit them consecutively, if both ports are visited. The algorithm checks if the route contains both of the ports in the adjoining pair, and if yes, only allows candidate routes where they are visited right after each other. Note that both ports in the adjoining pair may be visited before the other.

Lastly, to create routes that are efficient and may be more understandable for the



(a) Example of a feasible route which turns two times.

(b) Example of an infeasible route which turns three times.

Figure 6.2: Illustration of the concept of ”zigzagging” in the north/south direction.

passengers, the fifth rule disallows ”zigzagging” in the north/south direction. Since the routes are cyclic and not necessarily start in the most northern or southern ports, we allow them to turn twice, e.g. the route first goes south, then north and then south again. If the route turns more than two times, it is deemed infeasible and is discarded. An illustration of the concept is displayed in Figure 6.2. The rule is based on the ports having an attribute related to level in the north/south direction, similar to latitude. When a ferry on a route travels between ports, the level either increases, decreases or remains the same, depending on the port attributes. A turn in the route is then defined as the change from an increasing or decreasing level to the opposite.

Note that, the concept of zigzagging is allowed in the east/west direction due to the geographical attributes of the fjord considered in this thesis. The benefits of utilising a ferry instead of alternative transportation is larger when traveling across the fjord rather than along it, because of the differences in transit times. Moreover, when the ferry travels along the fjord, zigzagging in the east/west direction will not impose great detours. This rule can be adjusted to consider zigzagging in another direction if deemed relevant in the specific case study conducted.

On a final note, we present a route heuristic in Appendix B, which can be applied to decrease the set of candidate routes even further, and thus also the computational time required to solve the FSNDP. It provides good solutions, but since the current test instances are solved within reasonable time, we choose not to apply it in this thesis. Note that the computational time required to perform the route generation procedure is almost unaffected with the route heuristic, which may be challenging for larger port instances.

Combination of Route and Frequency Rule

We recall that the different *rf*-combinations yield different waiting times as described by Equation 5.9. Some combinations of route and frequency may be undesirable due to excessively long waiting times, implying poorer ferry utilization. Therefore, we impose a generation rule of maximum waiting time to remove these inefficient combinations, thereby also reducing the number of variables in the problem. The maximum allowed waiting time between round trips is denoted W^{Max}.

6.2.2 Generation Algorithm

Our generation approach and algorithm are presented in the following subsection. Initially, the candidate routes are generated according to the rules elaborated in Subsection 6.2.1, and a pseudocode of the route generation procedure is given in Algorithm 1. We choose to apply ”large” ports as theoretical starting ports to abide by rules one and three. The procedure constructs routes iteratively by extending the length of the route by one port per iteration, checking the feasibility of the extended route, and if it is feasible, the extended route is added to the set of feasible routes. As an example, the first iteration generates routes with two unique ports. Then, a third port is added to each of these routes, checked for feasibility according to the rules mentioned above, and if the new route is deemed feasible, it is saved as a candidate route. By only extending routes which are in themselves feasible, we avoid enumerating all permutations of the routes, thereby decreasing the computational time required to generate the routes. One exception to the feasibility requirement concerns routes with equal last and second last visit, e.g. $[A, B, A, A]$. These have to be temporarily feasible to construct other routes, e.g. $[A, B, A, C, A]$, but they will be discarded after they have been extended, such that they are not considered candidate routes.

After generating the candidate routes, the rule concerning maximum waiting time between departures for *rf*-combinations is imposed. The pseudocode is displayed in Algorithm 2, and it simply iterates through all combinations to eliminate those with too long waiting times. After completing both generation procedures, the set of candidate routes and frequencies is evaluated in the optimization model as described in Chapter 5.

Algorithm 1: Algorithm for describing the route generation procedure.

```
Initialize set of construction ports as all ports;
for all large ports do
    create initial set of candidate routes by combining this port with each of
      the ports in the set of construction ports, except itself;
    for routes in the set of candidate routes do
        for ports in the set of construction ports do
            extend the route with considered port;
            if the extended route is feasible by all rules then
                save the route in the set of candidate routes;
            else
                go to next route;
            end
        end
    end
    finished creating routes with this large port, remove it from the set of
      construction ports;
end
```

Algorithm 2: Algorithm for the procedure of the maximum waiting time rule.

```
for all combinations of route and frequency do
    Calculate the waiting time between departures;
    if waiting time $> W^{Max}$ then
        Discard this combination;
    end
end
```

Chapter 7

Test Instances and Implementation

In this chapter, we elaborate the implementation of the FSNDP, both regarding the mathematical model presented in Chapter 5 and the route generation procedure presented in Chapter 6. We present the test instances used for the computational study, which will be presented in Chapter 8. Firstly, in Section 7.1, we present the different test cases we will analyze. Section 7.2 further presents the numerical values of the parameters used for the test instances. Lastly, in Section 7.3, we sum up by providing an overview of the test instances and their naming.

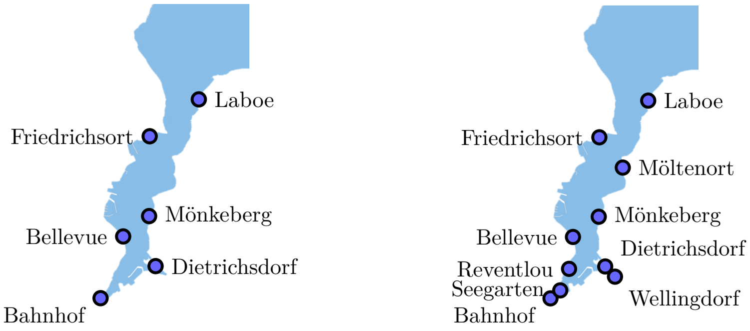
7.1 Test Cases

Some key parameters are subjected to a sensitivity analysis when testing. These are; the set of ports, the minimum required departure frequencies, the fleet size, and the maximum number of unique routes. Therefore, for each of the key parameters we present different cases, which will form the test instances.

7.1.1 Ports

We present two different port cases, *reduced* and *full*. The *full* port case comprises all the ports in use today on both Ferry line 1 and Ferry line 2, yielding a case with ten ports, thereby excluding the seasonal ports. The *reduced* case creates an alternative that covers the whole fjord, but with fewer port visits, and thus it comprises six of the ten ports spread evenly across the fjord. The two cases are visualized in Figure 7.1.

Table 7.1 displays all ports used for the two cases along with their relevant attributes, where the ports are assigned a number in the first column to ease the naming of routes. Moreover, the ports are either ”small” (S), ”medium” (M), or



(a) Ports included in the *reduced* port case.

(b) Ports included in the *full* port case.

Figure 7.1: Illustration of the two port cases.

"large" (L), which should reflect the demand from and to that port, and some ports are classified as "well connected" (*Well con.*), which are port pairs with excellent alternative transportation options, so the demand is reduced between these ports. For instance, passengers may prefer to walk between two ports if they are located close to each other, which would imply lower demand for the ferry system. Adjoining ports (*Adj.*) are located directly next to each other, and this attribute is used in the generation of routes. Furthermore, the ports have a defined location in the north/south (N/S) direction, which is related to their position on the map, and this attribute is also used in the route generation. A higher number implies the port is located further to the north in the fjord. Note that well connected and adjoining ports are referenced by the port number, not the port name, to ease readability.

We let the set of potential waiting ports be equal to the set of large ports, implying that $\mathcal{P}_r^{\mathcal{W}}$ as defined in Section 5.3 corresponds to all the large ports and port calls in the selected route. This affects the preprocessing procedure and the choice of waiting ports.

7.1.2 Minimum Required Frequencies

We construct two different cases for the minimum required frequencies per OD-pair. The first case equals no use of the minimum required frequencies, i.e. disregarding Constraints 5.3. The second case ensures most OD-pairs in the network have at least one departure per hour, and some OD-pairs will have more than one departure per hour. The minimum required frequency per OD-pair depends on the destination port size, and the imposed frequency per destination port size is displayed in Table 7.2.

For well connected ports, the required frequency is set to zero, meaning we do not impose any requirement of visits between ports that have good alternative transportation. However, note that there may still exist demand between these

Table 7.1: Description of attributes of the ports used in the test instances.

No.	Port name	Size	Well con.	Adj.	N/S
0	Laboe	L	-	-	7
1	Möltenort	M	-	-	5
2	Mönkeberg	M	-	-	4
3	Dietrichsdorf	L	4	4	2
4	Wellingdorf	L	3	3	2
5	Bahnhof	L	6, 7	6	0
6	Seegarten	S	5, 7, 8	5	1
7	Reventlou	L	5, 6, 8	8	2
8	Bellevue	S	6, 7	7	3
9	Friedrichsort	M	-	-	6

ports, so the solution may offer a departure between the ports. The key aspect is that the solution is not *required* to offer a departure.

Table 7.2: Minimum required frequency cases for the test instances.

Case	Small port	Medium port	Large port
Disregarded	0	0	0
Imposed	1	2	3

7.1.3 Fleet Size

Furthermore, the size of the fleet is of importance when solving the optimization problem. We solve the problem for a various number of available ferries, i.e. different values of V, as defined in Section 5.2. The test instances are solved with the cases of 10, 20, and 30 ferries available, and the case of 20 ferries is used as the base case.

7.1.4 Unique Routes

Lastly, we solve the model for different values of R^{Max}, which we recall from Section 5.2 is the maximum allowed number of unique routes in the solution. We define a case with only three unique routes, a case with six unique routes, and a case with nine unique routes.

7.2 Parameters

In this section, the parameters which are independent of the different cases, are presented. These are mainly parameters related to transit times, available departure frequencies, the utility function in the objective, and demand.

7.2.1 Transit Times

We assume equal speed for all ferries, and for all distances in the routes. Thus, the transit times of the routes only depend on the distances they include, not the ferry type nor the frequency. The sailing speed for our instances was calculated using an average sailing speed from the current time table of the ferry service in Kiel, and it is set to $S = 17$ km/hour.

To calculate the direct transit times between all port pairs, *Google Maps* was used to find the distances between each port pair i and j, L_{ij}^{Direct} (km). The distances were not always a straight line, but we retrieved the shortest distance that yielded a reasonable path given the restrictions of the fjord. Thus, the direct transit time between the same port pair, T_{ij}^{Direct}, was calculated by dividing the distance by the speed, as stated in Equation 7.1. The distances used in our tests are displayed in Appendix C.

$$T_{ij}^{Direct} = \frac{L_{ij}^{Direct}}{S} \tag{7.1}$$

Moreover, the round trip time for a route r, T_r, was calculated by adding the direct transit times, T_{ij}^{Direct}, between all the ports along the route, and the berthing time, T^{Berth} for each stop. Based on empirical measurements conducted during a field trip to Kiel, T^{Berth} is set to a constant of three minutes. In our instances we let T^{Berth} be independent of the number of passengers (dis)embarking, the ferry type and the port the ferry berths in.

We define $T_{rfimjnk}$ as the (indirect) transit time between ports i and j with port calls m and n in an *rf*-combination with waiting port and port call k. To calculate this value, we start by performing the same procedure as with the round trip time, though only considering the ports between the ports i and j with port calls m and n in route r. Then, an additional step of adding the waiting time is performed. Recall that the waiting time is incurred in the port and port call determined in the preprocessing procedure, as described in Section 5.3. If a passenger travels on a ferry service which is required to wait underway, this waiting time is added to the transit time, $T_{rfimjnk}$, of the passenger.

Recall from Section 5.2 that A_{rfij} states if an *rf*-combination is classified to serve passengers traveling from port i to port j, and if yes, how many times during the route r the OD-pair is served, including all port calls. A connection exists between two ports if both ports are in the route r. However, to avoid incurring too much excess transit time, we impose a maximum percent of excess transit time, Q^{Max}. The OD-pair is only defined as being served by the *rf*-combination if the transit time between the ports, T_{rfimjn}, is less than $(1 + Q^{Max})T_{ij}^{Direct}$, and thus Q^{Max} defines A_{rfij}. Q^{Max} is set to 100%, i.e $Q^{Max} = 1$. We deem it reasonable to avoid passengers traveling more than double of the direct transit time, because a large detour should imply that they prefer traveling by another route or mode of

Table 7.3: Numerical values of parameters associated with transit times for the FSNDP test instances.

Parameter	**Symbol**	**Values**
Sailing speed	S	17 $km/hour$
Berthing time	T^{Berth}	3 $minutes$
Maximum percentage ofexcess transit time	Q^{Max}	1

transportation. An overview of the numerical values of the parameters presented is given in Table 7.3.

7.2.2 Available Departure Frequencies

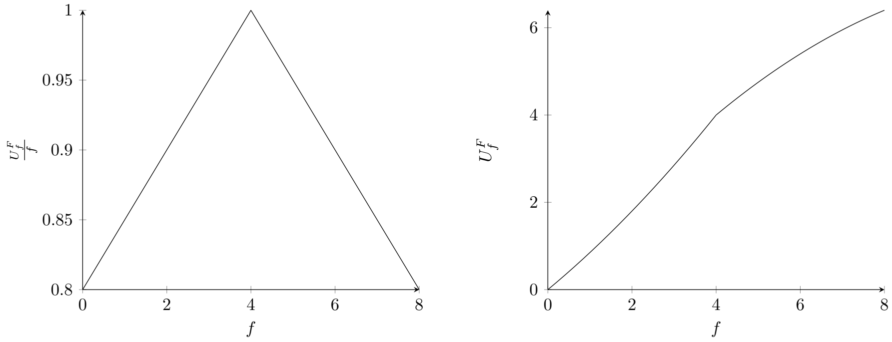
The departure frequencies deemed feasible for the model are restricted, because the ferry service aims to provide somewhat understandable schedules. For example, a frequency of seven times per hour would yield a route that departs every 8.57 minutes, which is not very intuitive. However, a frequency of six times per hour, would depart every tenth minute. Thus, the available departure frequencies ($departures/hour$) for the *rf*-combinations are 1, 2, 3, 4, 5, 6, and 8 implying the ferry visits the ports every 60, 30, 20, 15, 12, 10 and 7.5 minutes.

7.2.3 Utility Parameters

In our model, as elaborated on in Subsection 5.2.2 and Section 5.3, we define the utility for an *rf*-combination, U_{rf}, as described in Equation 5.15. The aim is to represent the trade-off between decreased transit time and increased departure frequency, weighted by demand on the different connections, such that the ferry network offers excellent customer service. We base our utility functions on prospect theory, a concept introduced by Tversky and Kahneman (1979), in which utility is defined over relative gains or losses from a reference point. They denote this a *value function.* As an example, the difference between winning nothing and 100$ is greater than the difference between winning 100$ and 200$.

Since increasing the excess transit time is viewed as a loss for the passengers, the utility decreases for larger values of excess transit time. We assume that passengers have their reference point for excess transit time around 40%, so when decreasing it even further, the marginal increase in utility is reduced. Thus, the passengers start to prefer frequent departures. These preferences could be justified by the modeling of a public transportation network, as passengers know they make use of a public offering, implying that they to some extent are willing to accept a detour on their journey, if they have many options to travel, i.e. frequent departures. The above mentioned features can be incorporated in the model by formulation of U_f^F and U_{rfijk}^T as follows.

Firstly, we define the frequency utility, U_f^F, as shown in Equation 7.2. Here we assume that the marginal utility from higher departure frequencies diminishes after



(a) Frequency utility per departure.

(b) Total value of U_f^F for a frequency.

Figure 7.2: Visualization of the frequency utility.

four departures per hour, which implies that the utility per departure reaches its maximum at this departure rate, as visualized in Figure 7.2a. The figure shows the utility *per departure* given a departure rate f. The resulting total utility for a given departure frequency, f, is displayed in Figure 7.2b. This nonlinear valuation of departure frequencies gives incentives to offer two different routes with frequency around four times per hour, instead of a single route with frequency eight times per hour. Thus, we aim to construct a network with more connections between the ports.

$$U_f^F = \begin{cases} f \cdot (0.05\,f + 0.8), & \text{if } f \leq 4 \\ f \cdot (-0.05\,f + 1.2), & \text{if } 4 < f \leq 8 \\ 0, & \text{otherwise} \end{cases} \tag{7.2}$$

Secondly, recall U_{rfijk}^T is the utility associated with excess transit time from port i to port j in route r with frequency f and waiting port and port call k. As previously stated, we assume that passengers accept some level of excess transit time, and therefore, the utility decreases nonlinearly, where the marginal decrease in utility with respect to excess transit time increases with higher excess transit times before flattening out around 60% excess. We place the inflection point around 40%. This implies that the difference in utility is larger between 50% and 40% excess transit time than for 20% and 10%, corresponding to the assumptions regarding passenger preferences. As a result, we aim to construct a ferry network which reduces the spread in excess transit time between passengers. Though we base the shape of the utility function on Tversky and Kahneman (1979), the exact formula has been formulated for the assumptions of passenger transportation considered in this thesis.

Let M_i be the number of port calls to i, i.e. the total number of visits to port i, in route r, and let N_j be corresponding number for port j. Then, the utility

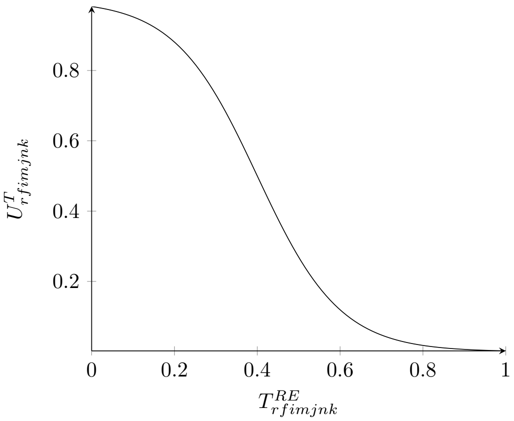


Figure 7.3: Visualization of the transit time utility.

function, U^T_{rfijk}, is described by Equation 7.3. U^T_{rfijk} is a mean over m and n of $U^T_{rfimjnk}$, where $U^T_{rfimjnk}$ is the utility associated with traveling between i and j with port calls m and n on the route of an rf-combination with waiting port and port call k. $U^T_{rfimjnk}$ is calculated by Equation 7.4. Since this utility is based on the excess transit time, denoted $T^{RE}_{rfimjnk}$, we calculate it by Equation 7.5. The value of $U^T_{rfimjnk}$ for different $T^{RE}_{rfimjnk}$ is presented in Figure 7.3 to illustrate the relations between excess transit time and corresponding utility. Note that the effect of the utility function is limited by the parameter **A** in the objective, so if the excess transit time is above Q^{Max}, it will not incur any utility.

$$U^T_{rfijk} = \frac{\sum_{m=1}^{M_i} \sum_{n=1}^{N_j} U^T_{rfimjnk}}{M_i \cdot N_j} \tag{7.3}$$

$$U^T_{rfimjnk} = \frac{1}{e^{-4+10 \cdot T^{RE}_{rfimjnk}} + 1} \tag{7.4}$$

$$T^{RE}_{rfimjnk} = \frac{T_{rfimjnk} - T^{Direct}_{ij}}{T^{Direct}_{ij}} \tag{7.5}$$

7.2.4 Demand

Moreover, we construct demand samples which are randomly drawn from a distribution. We sample a random demand for each OD-pair from the uniform distribution on the interval [50, 100]. Similar to the minimum required frequencies, the demands are adjusted to account for differences in port size, however both with respect to the origin and the destination port. Each sampled OD-pair demand is multiplied with the product of two factors. The first factor relates to the origin port in the OD-pair, and it is set to 0.75 for small, 1.00 for medium and 1.25 for large ports. The second factor depends on the destination port in the OD-pair, where small ports get factor 0.5, medium ports factor 1.0 and large ports factor 1.5. Furthermore, independent of port size, the demand between well connected ports is decreased by 90% (factor 0.1). Thus in total, the demand is either increased or decreased based on the port attributes.

We present a small example to display how a sample of the demand is constructed. For the *full* port case, the demand matrix is size ten by ten. Each element in this matrix represents an OD-pair, and the diagonal is set to zero. For each OD-pair in the matrix, we sample a random number uniformly on the interval [50, 100]. Then, we evaluate the attributes of that OD-pair. If we are evaluating the ports of Seegarten and Reventlou, the OD-pair concerns well connected ports which are small and large, respectively. This implies that the sampled random number, e.g. 70, is multiplied by 0.1, 0.75 and 1.5. The resulting demand for the OD-pair of Seegarten and Reventlou is 7.875 which is rounded to the nearest integer of 8. One demand sample is given in Table D.2, and an average of five demand samples is displayed in Table D.1. Note that the total average demand between all ports for the *full* port case is approximately 8,339 passengers per hour.

7.3 Instances

All test instances were run with the same parameters presented in Section 7.2. However, the difference in test instances stems from the included cases. A test instance is based on the choice of case with respect to ports, minimum required frequency, fleet size, and maximum number of routes, as described in Section 7.1. The test instances considered in this thesis for the FSNDP are presented in Table 7.4.

We mainly want to analyze the effects of changing one case at a time, and therefore, we choose a base case combination of cases, which we compare with other instances where one case has been changed at a time. The base case of ports will be the *full* case, and the fleet size base case is 20 ferries. The base case of maximum routes is six, and for the minimum required frequencies, we choose to always evaluate both cases, thereby not assigning a base case. Thus, the base case test instances are Full-Imp-20-6 and Full-Dis-20-6.

Table 7.4: Overview of the FSNDP test instances.

Instance	**Port case**	**Minimum frequency**	**Fleet size**	**Unique routes**
Full port case				
Full-Imp-10-6	Full	Imposed	10	6
Full-Imp-20-3	Full	Imposed	20	3
Full-Imp-20-6	Full	Imposed	20	6
Full-Imp-20-9	Full	Imposed	20	9
Full-Imp-30-6	Full	Imposed	30	6
Full-Dis-10-6	Full	Disregarded	10	6
Full-Dis-20-3	Full	Disregarded	20	3
Full-Dis-20-6	Full	Disregarded	20	6
Full-Dis-20-9	Full	Disregarded	20	9
Full-Dis-30-6	Full	Disregarded	30	6
Reduced port case				
Red-Imp-10-6	Reduced	Imposed	10	6
Red-Imp-20-6	Reduced	Imposed	20	6
Red-Dis-10-6	Reduced	Disregarded	10	6
Red-Dis-20-6	Reduced	Disregarded	20	6

Chapter 8

Computational Study I

The following chapter presents a computational study of the FSNDP. First, we present an analysis of the test instances with respect to computational efficiency in Section 8.1. Then, the FSNDP is subject to a bi-objective analysis in Section 8.2. Lastly, we provide managerial insights based on analyses of all test instances, and these are presented in Section 8.3. This section also includes a comparison between the current ferry service in the Kiel fjord and preliminary conclusions for the FSNDP.

The computational study has been implemented using PyCharm version 2019.3.3 64-bit with Python 3.7. PyCharm offers an integrated platform to generate large data files, create complex functions and structure a network of programming files. The mathematical model has also been implemented using PyCharm, and the commercial optimization solver Gurobi Optimizer version 9.0.1 was imported to compute the solutions. We performed all tests for the FSNDP on a computer with a 2.7GHz Intel Core i5 processor and 8GB RAM, which runs the Mac OS X El Capitan (version 10.11.6) operating system.

8.1 Computational Efficiency

This section presents a technical analysis of the results with respect to some key attributes, including objective value, solution time and sample variance.

The *rf*-combination generation procedure presented in Section 6.2 has been implemented, and for the *reduced* port case 473 routes are generated, which results in 2,177 candidate combinations. The procedure takes a few seconds. For the *full* port case 257,400 routes are generated, which yields 1,155,059 candidate combinations in approximately half an hour. Even with the heuristic rules, the generation procedure experiences a combinatorial explosion, where an increase from six to ten ports, i.e. a 67% increase in the number of ports, resulted in a 430% increase in the

Table 8.1: Technical solution attributes for the test instances of the FSNDP. Infeasible test instances are marked with ”-”.

Instance	**Obj. value**	**CV obj.**	**Gurobi time,** *min*	**CV time**
Full port case				
Full-Imp-10-6	-	-	42.0	7.9%
Full-Imp-20-3	42,578	1.3 %	51.9	113.0 %
Full-Imp-20-6	47,980	1.5 %	21.0	18.5 %
Full-Imp-20-9	49,636	1.4 %	22.8	18.0 %
Full-Imp-30-6	72,329	1.4 %	11.1	24.5 %
Full-Dis-10-6	26,765	1.4 %	3.6	2.9 %
Full-Dis-20-3	48,909	1.4 %	3.5	7.8 %
Full-Dis-20-6	50,784	1.3 %	3.5	10.1 %
Full-Dis-20-9	52,134	1.3 %	3.7	3.8 %
Full-Dis-30-6	74,253	1.5 %	4.8	7.7 %
Reduced port case				
Red-Imp-10-6	15,396	2.9 %	0.005	13.8 %
Red-Imp-20-6	31,261	3.2 %	0.004	8.0 %
Red-Dis-10-6	17,396	1.6 %	0.001	4.9 %
Red-Dis-10-6	31,302	2.6 %	0.001	11.8 %

candidate combinations. Both when running the test instances for the *reduced* and the *full* port case, all instances are solved to optimality, unless they are infeasible.

All test instances have been computed five times, with different demand samples. Average values of the five demand samples are given in Table D.1. The coefficient of variance (CV) for each OD-pair is calculated as the ratio of the standard deviation and the mean of the demand for the OD-pair across the samples. The average CV for all OD-pairs in the *full* port case is 16.5%.

Table 8.1 displays selected technical attributes when solving the test instances for the FSNDP. The first column (*Instance*) displays the test instance considered. The next column (*Obj. value*) displays the objective values, while the third column (*CV obj.*) displays the (CV) of the objective values for the different samples. The two last columns (*Gurobi time*, *CV time*) display the computational time required for the optimization solver Gurobi in minutes, i.e. excluding the preprocessing procedure, and the coefficient of variance for this run time. The coefficient of variance is calculated as described above, by the ratio of the standard deviation between the test instances with different demand samples to the mean of the instances.

As expected, the objective value increases with larger fleet size, relaxed frequency requirements, and more unique routes, as these changes increase the solution space. Moreover, we notice that the objective values are higher for the *full* port case, due to the inclusion of more demand. In the case of only 10 ferries, with requirements on the minimum frequencies, and the *full* port case, i.e. Full-Imp-10-6, the model is not able to find a feasible solution. This implies that 10 ferries are not enough to serve all ten ports with the given frequency requirements.

From Table 8.1 we observe that the coefficient of variance for the objective does not vary significantly between the different cases. Since all instances are solved to optimality, the variation in the objective values only depends on the variation of demand in the different samples. The coefficient of variance for the objective in the *full* port case is around 1.4% and when compared to the coefficient of variance for the demand itself, 16.5%, the objective variance seems significantly reduced. This implies that the model is less sensitive for smaller variations in demand, which may be due to an ”evening out” of utility. One demand sample may have lower demand for a given OD-pair compared to another sample, but the total demand over all OD-pairs remains fairly stable, because all samples are drawn from the same distribution. Thus, the model may find another ferry schedule which services different demand with approximately the same utility. However, we notice that the *reduced* port case is somewhat more sensitive to changes in demand than the *full* port case, because the total demand between samples may vary more when fewer ports are included, thereby reducing the chance of identifying equally good solutions.

Furthermore, the run times for instance Full-Imp-20-3 vary significantly. In this particular case, there was one test instance that required much higher run time with Gurobi than the four others. This may be due to this particular case of input parameters presenting an unfortunate combination for the Gurobi solver algorithm. The average run time for the four other test instances was 22.6 minutes in Gurobi with a coefficient of variance of 3.7%, which corresponds more to the results from the other test instances.

Next, we see from Table 8.1 that the computational times are small for the *reduced* port case. For the *full* port case, with four more ports, the run times are significantly increased. This implies that the solution times scale quite poorly, which we anticipated due to the combinatorial explosion in the route generation, thereby also the decision variables. For a strategic problem, all of these run times are acceptable, but for larger port cases, heuristics may be necessary. Furthermore, we note that the minimum frequency requirement has the greatest impact on run time. This is natural, as these constraints add to the complexity of the solution space, when the model attempts to identify the trade-off between total frequency and transit time whilst satisfying the minimum frequencies. The remaining cases of fleet size and maximum number of routes do not seem to have an unambiguous effect on the run time in Gurobi.

Recall from Section 5.3, that we have a preprocessing procedure, where we determine the waiting ports and port calls in all routes. Since the routes are the same within a port case, and due to the nature of the preprocessing procedure, this procedure only depends on the port case and demand sample of the test instances. Thus, the preprocess time did not vary within a port case, and for our testing the average preprocess time for the *full* port case was 148 minutes, with a coefficient of variance of 6.4% between the demand samples, while for the *reduced* port case, the average preprocess time was 0.09 minutes with a coefficient of variance of 5.3%. We notice that the preprocessing is quite time consuming compared to the solving of the model, because the waiting port and port call is determined for all candidate rf-combinations.

8.2 Bi-Objective Analysis

In this section, we perform a bi-objective analysis of the optimization model presented in Chapter 5. Recall from Subsection 5.2.2 that the objective function consists of a constructed utility related to the departure frequency and excess transit time. By separating the objective with respect to these utilities, we get a multi-objective optimization problem with two objectives.

Multi-objective optimization problems (MOOPs) have objective functions that constitute a multidimensional space, and they result in several trade-off solutions (Deb, 2005). Thus, identifying the best solution to a MOOP represents a trade-off between objectives, in contrast to single objective problems (SOPs) where a unique optimal solution exists. The trade-off solutions are denoted Pareto-optimal solutions, and each Pareto-optimal solution must be no worse than any other solution in all objectives and strictly better than any other solution in at least one objective. By identifying the set of Pareto-optimal solutions, the Pareto front can be obtained, on which the equivalent solutions are located.

To inspect the trade-off between departure frequencies and excess transit time in the solutions, we define our bi-objective problem as follows. Equation 8.1 and Equation 8.2 represent the utility related to the departure frequency and excess transit time, respectively. Both terms are related to the demand between each OD-pair, and the parameter **A** ensures that utility related to OD-pairs with more than 100% excess transit time are disregarded.

$$U^{Frequency} = \sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} \sum_{(i,j) \in \mathcal{P}} A_{rfij}\, D_{ij}\, U^F_f\, x_{rf} \tag{8.1}$$

$$U^{Time} = \sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}_r} \sum_{(i,j) \in \mathcal{P}} A_{rfij}\, D_{ij}\, U^T_{rfij}\, x_{rf} \tag{8.2}$$

The Pareto front is identified by applying the *weighted-sum approach*, as presented by Deb (2005). The bi-objective problem for the FSNDP is formulated by Equation 8.3 and Constraints 8.4. Weighting parameters, λ_F and λ_T, are introduced in the objective, and they have two properties. First, they sum to one, and second, they must be non-negative. λ_F relates to the utility of frequency, while λ_T is used for the utility of excess transit time. Each objective weight is multiplied by 2 to ensure that $\lambda_F = \lambda_T = 0.5$ equals the original formulation. Constraints 8.4 represent all

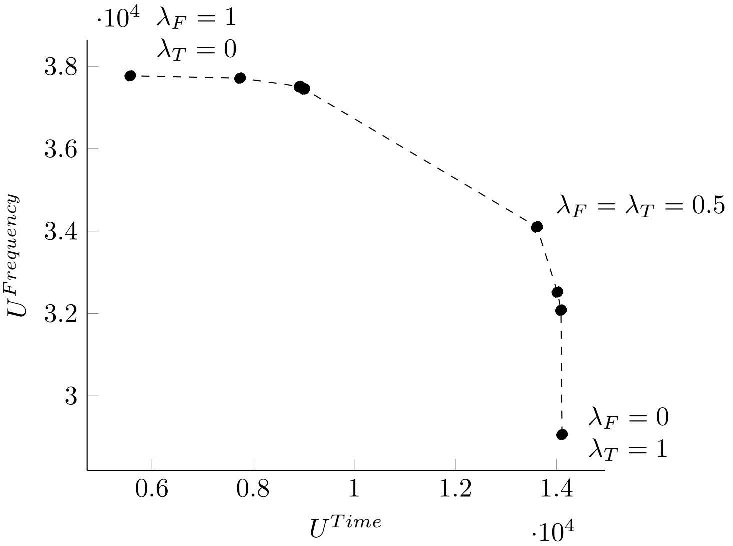


Figure 8.1: Approximated Pareto front for the Full-Imp-20-6 instance with utility related to the departure frequency and excess transit time for various values of λ_F and λ_T.

the constraints of the original mathematical formulation, i.e. Constraints 5.3-5.7 in Chapter 5.

$$\max z = 2\lambda_F \, U^{Frequency} + 2\lambda_T \, U^{Time} \quad (8.3)$$

$$\text{s.t.} \quad x \in \mathcal{X} \quad (8.4)$$

The model is tested for instance Full-Imp-20-6 with a single demand sample, which is the average of five samples. Figure 8.1 displays the resulting approximated Pareto front for $\lambda_F, \lambda_T \in [0,1]$ with step length 0.05. The front appears concave, and since both objectives are maximized, the graph illustrates the conflicting objectives.

Due to the objectives representing a constructed utility, we present some more tangible solution attributes in Figure 8.2 to evaluate the effects of the utility functions. The graph displays the average departure frequency between each OD-pair per hour, weighted by demand for the respective OD-pair, compared to the relative average excess transit time, weighted by both the frequency and demand of each OD-pair. Both values are calculated with parameter **A**, which implies that all OD-pairs with excess transit time less than 100% are included.

Due to the aim of maximizing departure frequency and minimizing excess transit time, there exists a trade-off between the two objectives, which we modeled by the utility functions. Generally, a higher departure frequency in the network implies

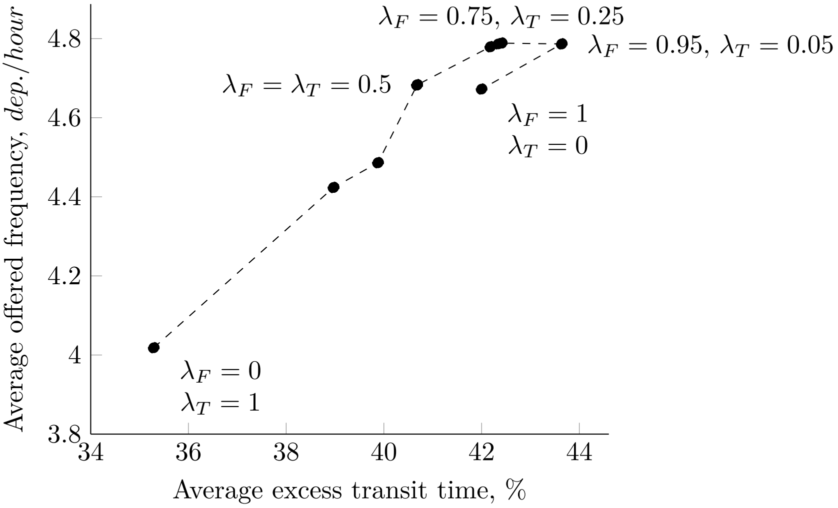


Figure 8.2: Average departure frequency per hour compared to the average excess transit time per passenger for various values of λ for the *full* port case test instance.

increased excess transit times, because the ferries will prioritize visiting more ports rather than offering more direct routes. By mapping the solutions to the more tangible solution attributes, it appears that the utility functions work as intended. In Figure 8.2 the graph increases almost linearly between $\lambda_F = 0$ and $\lambda_F = 0.75$. The cases of $\lambda_F = 1$ and $\lambda_F = 0.95$ are dominated by $\lambda_F = 0.5$ and $\lambda_F = 0.75$ respectively, because the dominated solutions have marginally lower average offered frequency with higher excess transit time. The dominated solutions may be caused by the fact that the FSNDP objective does not consider these solution attributes directly. Thus, if we consider the selected solution attributes, the trade-off between departure frequency and excess transit time is best represented by the utility functions until $\lambda_F = 0.75$.

The operator may choose the desired solution based on the presented trade-off. For the remainder of the thesis, we use $\lambda_F = \lambda_T = 0.5$, which corresponds to the original formulation presented in Chapter 5.

8.3 Managerial Insights

In this section, we analyze and discuss some managerial insights related to the results of running the test instances. Firstly, we provide some stand-alone analyses of the performance of the FSNDP. Secondly in Subsection 8.3.1, we compare the FSNDP solutions to the current offering in Kiel, and lastly in Subsection 8.3.2, we draw some preliminary conclusions for the FSNDP.

Table 8.2 displays selected managerial attributes of the test instance solutions. All

Table 8.2: Managerial solution attributes for test instances of the FSNDP. Infeasible test instances are marked with ”-”.

Instance	**Unique routes**	**Average frequency**	**Average call per port**	**Average excess t.t., %**	**Unserved OD-pairs**
Full port case					
Full-Imp-10-6	-	-	-	-	-
Full-Imp-20-3	3	4.6	11.3	42 %	0
Full-Imp-20-6	6	4.7	11.5	41 %	0
Full-Imp-20-9	9	4.5	11.6	39 %	0
Full-Imp-30-6	6	7.4	17.1	44 %	0
Full-Dis-10-6	6	2.3	6.0	37 %	21.6
Full-Dis-20-3	3	5.2	11.4	45 %	3.6
Full-Dis-20-6	6	5.0	11.2	43 %	0
Full-Dis-20-9	9	4.7	11.1	41 %	0
Full-Dis-30-6	6	7.7	16.9	45 %	0.4
Reduced port case					
Red-Imp-10-6	3	4.0	6.8	34 %	0
Red-Imp-20-6	5	7.9	13.0	31 %	0
Red-Dis-10-6	5	3.6	5.9	29 %	0
Red-Dis-20-6	5	7.9	13.0	32 %	0

values are averages of the same test instance computed with five different demand samples. The first column (*Instance*) states the instance considered. Furthermore, the second column (*Unique routes*) displays the number of unique routes in the solution. The third column (*Average frequency*) states the average frequency offered between each OD-pair in the network, weighted by the respective demand and limited by the excess transit time requirement imposed by parameter **A**. Thus, OD-pair connections with too long excess transit times are not included. The fourth column (*Average call per port*) displays the average number of visits per port during an hour. The fifth column (*Average excess t.t.*) displays the average relative excess transit time per passenger considering all connections offered between the OD-pairs across all routes, weighted by the frequency of the respective route and the demand of the respective OD-pair. Note that this solution attribute also is limited by the excess transit time requirement. The last column (*Unserved OD-pairs*) displays how many OD-pair connections that are not included in any route in the solution network, i.e. it is impossible to travel between the ports without transfer regardless of the excess transit time of the passenger.

From Table 8.2 we observe that the maximum number of unique routes always is a binding constraint for the *full* port case. Moreover, the solution quality for different values of R^{Max} changes only slightly with respect to average frequency and excess transit time. Thus, the complexity of the network may be reduced without affecting the service quality significantly. Furthermore, we notice that the maximum number of unique routes is nonbinding in the *reduced* port case, given the same fleet sizes. With fewer ports to serve, fewer unique routes are required to offer an optimal level of service.

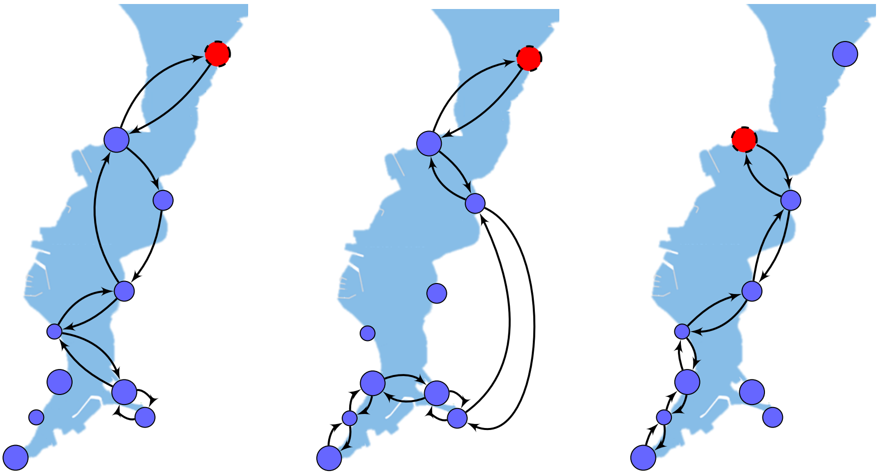
Interestingly, we see that the departure frequency is strongly affected by the number of ports, as we observe that the departure frequency increases from 4.7 to 7.9 when moving from instance Full-Imp-20-6 to Red-Imp-20-6. A similar observation holds for the test instances with *disregarded* frequencies. Moreover, we observe that the fleet size also significantly affects the average offered frequency between each OD-pair. It seems that the *reduced* port case can achieve about the same departure frequencies with 10 ferries less.

Moreover, for the *full* port case, we notice that the *imposed* case somewhat reduces the average frequency, which is natural, as it ensures the routes visit specific ports, even with lower demand. As an example, Full-Imp-20-3 serves all OD-pairs, while Full-Dis-20-3 has unserved OD-pairs, implying that the departure frequency is increased at the cost of not offering any service between some OD-pairs. Also, notice that for the *reduced* port case it appears 10 ferries is enough resources to cover the minimum frequency requirements without unserved OD-pairs. Moreover, 20 ferries seems to provide enough capacity in the network such that the minimum required frequencies do not affect the solution significantly. Therefore, it appears the model manages to diversify departures through the network without the need for the minimum required frequencies, if the fleet capacity is sufficient with respect to the number of included ports.

Furthermore, the average call per port, i.e. how many times each port on average is visited during an hour, is mostly affected by the number of ferries available and the port case. For Full-Imp-30-6 and Full-Dis-30-6 the average call per port is 17 times an hour, which implies a ferry will depart from every port on average every three and a half minute. With a berthing time of three minutes and few mooring points, congestion may occur with this departure frequency. Thus, for practical reasons in the Kiel fjord, 30 ferries seems too many. With only 10 ferries available, a ferry departs from each port every tenth minute, on average. This solution attribute does not reflect the spread of the departures, so ports with high demand may be visited more often than others.

Considering the average excess transit time, we notice that it increases slightly with a larger fleet size, which may not be expected at first glance. However, the differences appear insignificant to a passenger. For example, from Bahnhof to Laboe, the direct transit time is 40 minutes, implying that, with 37% excess transit time, the trip takes 55 minutes, while with 45% excess transit time, it is 58 minutes, which is only a three minutes difference. Also, recall that the utility functions defined by Equation 7.2 and Equation 7.3 aims to identify trade-offs between increasing the frequency and decreasing the excess transit time. Thus, the model appears to serve its purpose by prioritizing an increase in average frequency while ensuring an average excess transit time around 40% when changing the fleet size. The *reduced* port case seems to yield lower average excess transit times, while offering higher frequencies. The same fleet size with fewer ports to serve enable more direct links, thus reducing the excess transit time.

Moreover, notice that in the *disregarded* case, the number of unserved OD-pairs is significantly reduced with a larger fleet. Even though the average excess transit time is low in Full-Dis-10-6, it does not reflect that approximately 22 OD-pairs are not serviced at all. This is important when considering the level of customer service provided by the network. The *imposed* case has no unserved OD-pairs, because the case ensures departures between all OD-pairs. Therefore, with the limited fleet size and service requirements given by **A**, Full-Imp-10-6 is deemed infeasible. However, already at 20 ferries, the model identifies solutions with no unserved OD-pairs, both with and without the minimum frequency requirements, which is somewhat surprising. This also supports the observation that the model may spread departures in the network even without the minimum frequency requirements.



(a) First route with frequency three.

(b) Second route with frequency three.

(c) Third route with frequency three.

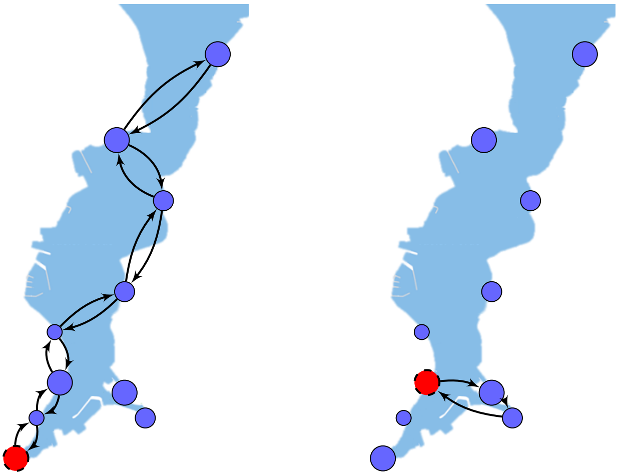
Figure 8.3: Illustration of the FSNDP solution with *full* port case and maximum three unique routes in the Kiel fjord, i.e. instance Full-Imp-20-3. The size of the node represents the size of the demand, and the dashed, red node marks the waiting port.

To embody our solutions, we present a visualization of a test instance solution, namely Full-Imp-20-3, in Figure 8.3. The solution network offers connections between all ports, as specified by the minimum frequencies, and the three different routes yield connections of different length. For example, a passenger may travel from the southern to the northern ports more directly using the second route. In addition, the frequency of each route is three, which is preferable, as specified by the frequency utility function. More detailed solution configurations for other selected test instances are displayed in Appendix E.

8.3.1 Comparison to Current Offering

In the following, we present a comparison between the proposed FSNDP network and the current ferry service as described in Chapter 2.

Based on the current ferry schedule, we reconstruct a ferry network that aims to replicate the current offering. Since Ferry line 1 changes slightly between departures, we have chosen to include the most frequently served route. This route and Ferry line 2 are visualized in Figure 8.4. Line 1 departs once per hour, while line 2 departs twice per hour. To ensure this departure frequency, four ferries must be deployed. Based on this ferry network, we calculate relevant solution attributes.

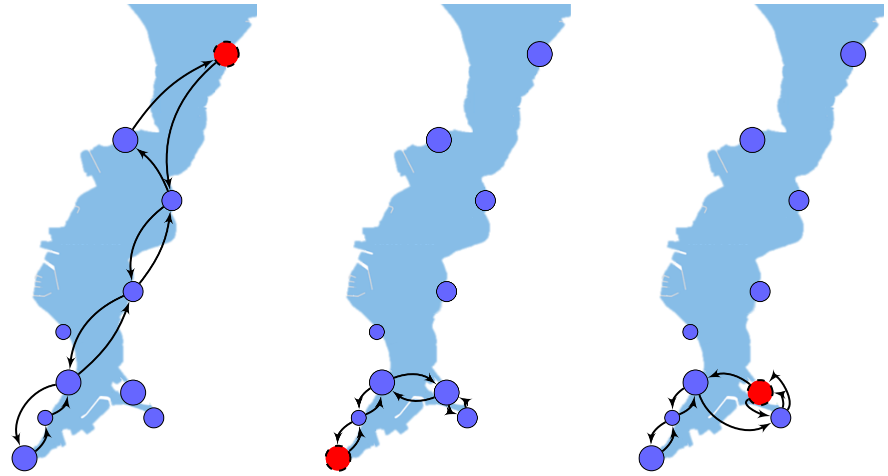


(a) Ferry line 1, once per hour.

(b) Ferry line 2, twice per hour.

Figure 8.4: Illustration of the current ferry service offering in the Kiel fjord. The size of the node represents the size of the demand, and the dashed, red node marks the waiting port.

For comparison, we solve the FSNDP with four ferries. Recall that the current ferry network does not offer connections between all ports without the use of transfer in the port of Reventlou. Therefore, when solving the FSNDP, we use the *disregarded* minimum required frequencies. Otherwise, the FSNDP would be infeasible due to Constraints 5.3, as these constraints can not be fulfilled with transfer. This implies the use of instance Full-Dis-4-6 with an average sample of demand. When solving this instance, we find that all four solution routes only include the five most southern ports. Thus, the solution network contains no visits to the ports above



(a) First route with frequency one. **(b)** Second route with frequency one. **(c)** Third route with frequency one.

Figure 8.5: Illustration of the test instance Full-Adap-4-6 in the Kiel fjord. The size of the node represents the size of the demand, and the dashed, red node marks the waiting port.

Reventlou, i.e. Bellevue, Mönkeberg, Möltenort, Friedrichsort and Laboe.

Since the proposed solution by the FSNDP without minimum required frequencies does not serve several ports in the north, including Laboe, we choose to present a solution of the FSNDP with adapted minimum required frequencies. We construct a minimum required frequency case, denoted *Adap*, which ensures one departure per hour between Laboe and Bahnhof, and two departures per hour between Dietrichsort and Reventlou. Thus, we construct a case which represents some key departures of the current offering. We solve the test instance Full-Adap-4-6 with an average sample of demand. The proposed solution is displayed in Figure 8.5, where each of the three solution routes is illustrated. Note that Bellevue is not visited in the proposed solution, which may be due to a too low demand in our demand generation procedure. However, the imposed minimum required frequency between Laboe and Bahnhof has ensured visits to all other ports in the network, thus displaying the potential to control key departures through minimum frequencies.

Table 8.3 displays the managerial solution attributes for the current offering and the FSNDP with the two different minimum frequency cases. The columns correspond to Table 8.2. The FSNDP test instance solutions offer more unique routes, but each of these routes is only offered once per hour. This network may appear somewhat confusing, so it is most suitable for digital schedule solutions where passengers find their journey through e.g. an app. Moreover, the average frequency per OD-pair

Table 8.3: Managerial solution attributes for the current offering and the comparison test instances.

Instance	Unique routes	Avg. frequency	Average call per port	Avg. overall excess relative t.t., %	Unserved OD-pairs
Current	2	0.73	2	40%	28
Full-Dis-4-6	4	0.95	3.3	33%	70
Full-Adap-4-6	3	0.88	2.7	32%	34

has increased for the FSNDP solutions, implying that the proposed model offer slightly more connections between high demand OD-pairs. This is also supported by the increase in average calls per port, which implies that more connections and departures are available in the network. However, the number of unserved OD-pairs has increased, especially in the *disregarded* case, which is partly due to the exclusion of Bellevue in the FSNDP solutions. Lastly, note that the average excess transit time of all passengers in the network decreases with the improved flexibility of the FSNDP. Therefore, the FSNDP appears to provide good solutions with respect to the chosen solution quality metrics, both considering increased departure frequency and decreased excess transit time for the passengers.

In addition, the two FSNDP test instances seem to display the trade-off between increased departure frequencies and unserved OD-pairs. Instance Full-Adap-4-6 shows that the number of unserved OD-pairs can be halved at the cost of only a slightly decreased average frequency, as both FSNDP instances display the same average relative excess transit time. Thus, the network connects more ports without major changes in the relative excess transit time with *imposed* minimum frequencies.

8.3.2 Preliminary Conclusions

This chapter has provided insights relating to the performance of the FSNDP as a decision support tool when designing a new fixed schedule ferry service network in the Kiel fjord. We observed that the time to generate candidate rf-combinations scaled somewhat poorly, and thus, the current model is not so suitable for larger port cases than ten ports. We attempted to solve a port case with 13 ports, but were not able to complete the route generation procedure even with the use of the proposed route heuristic. However, with a more effective route generation algorithm and preprocess structure, the FSNDP may most likely also provide decision support for larger instances due to the simplicity of the optimization model.

Since the FSNDP contains constructed bi-objective utilities, the objective value itself does not provide tangible solution attributes, but instead we have studied departure frequencies and excess transit time of the solutions. When comparing to the current offering in Kiel, we observed that with the same fleet, the FSNDP could achieve almost 30% higher average departure frequency per OD-pair and almost 18% lower average excess transit time per passenger. However, the OD-pair connections are fewer, and therefore, in order to achieve a ferry network that provides a high level of customer service without transfer using the FSNDP, the fleet size may have to be larger than what they currently have in Kiel.

The fleet size has a great impact on the performance of the ferry service. A fleet of 30 ferries seems too large due to congestion in the ports, but 20 ferries appears to provide good service in the fjord. For the instances with 20 ferries, the *imposed* minimum required frequencies did not affect the solution attributes to a large degree. However, a small number of unserved OD-pairs sometimes appear in the solutions without the minimum required frequencies. Therefore, it may seem like there is no need for the minimum required frequencies with a sufficiently large fleet, but the control over departures provided by these constraints, can help avoid undesired missing connections between OD-pairs. Moreover, the ability to ensure certain departures may reduce the need for the time-consuming step of identifying and fine-tuning the correct weighting and formulation of utility functions. The effect of the minimum required frequencies will be further analyzed in Chapter 12.

Moreover, we observed a trade-off between departure frequencies and excess transit time, where the model tends to choose somewhat higher transit times for a larger increase in departure frequencies. Thus, the model appears to serve its purpose by prioritizing an increase in average frequency while ensuring an average excess transit time around 40% when changing the fleet size. Other results can be achieved by tuning the utility functions, e.g. the inflection point of the transit time utility function. The restriction on the number of unique routes did not seem to reduce the solution quality much, which may provide some benefit regarding the construction of less complicated timetables.

We also noticed that the *reduced* port case often had higher departure frequencies and lower excess transit times with the same fleet size. One could argue that with fewer, more sought-after ports, the large demand from these ports will be served more efficiently. On the other hand, serving a greater set of ports implies that more passengers will have a ferry offering close to their desired origins and destinations.

Lastly, we want to emphasize that even though the FSNDP seems to provide good solutions, a model without tracking of load and capacity constraints gives a limited picture of the reality when computing solution attributes. Hence, the findings from the simulation conducted in Part II will provide deeper insights into the performance of the FSNDP.

Part II

Combined Dial-a-Ride and Fixed Schedule for a Ferry Service

In this part of the thesis, we present the Combined Dial-a-Ride and Fixed Schedule for a Ferry Service (C-DAR-FS) problem. This problem concerns a ferry service system with a fixed schedule service and an additional *dial-a-ride* service, henceforth denoted as DAR-service, where ferries may be rerouted after realized demand. The overall aim is to identify a good allocation of a given fleet of ferries between the two services. The ferries allocated to the DAR-service may provide increased customer service to the passengers through their flexible and responsive behavior, while the fixed schedule departures provide predictability. The problem is evaluated by a simulation system, which generates incoming requests, and we propose an assignment procedure to determine which ferry service should serve the request.

Recall from Chapter 1 that Part II is structured as follows. An overview of relevant literature is provided in Chapter 9. In Chapter 10 the modeling of the C-DAR-FS is described in further detail, and in Chapter 11 we present the insertion heuristic used when assigning a request to the DAR-service. Lastly, in Chapter 12, we present and discuss the results from different test instances in order to assess the C-DAR-FS.

Chapter 9

Literature Review II

In this chapter, we present a brief overview of relevant literature for the C-DAR-FS. Recall that general ferry network design literature was presented in Chapter 3. Thus, this chapter focuses on the new elements introduced for the C-DAR-FS. As the C-DAR-FS includes the use of a dial-a-ride (DAR) service, we present an overview of the dial-a-ride literature in Section 9.1. Moreover, since the C-DAR-FS is evaluated by a simulation system, we attempt to categorize the simulation system according to the literature concerning the combination of simulation and optimization methods in Section 9.2.

9.1 Dial-a-Ride

In this section, we provide a brief overview of the dial-a-ride problem (DARP). For a more comprehensive presentation of the DARP, the reader is referred to Ho et al. (2018), Molenbruch et al. (2017) and Cordeau and Laporte (2007).

We used the search engine Scopus to identify relevant literature, using two groups of search keywords. The first group relates to the DAR-service and includes ”dial-a-ride”, ”dial”, ”ride”, and ”dial-and-ride”, while the second group concerns more problem specific details discussed in this thesis, including ”simulate/simulation/simulating” and ”insert/insertion/inserting heuristic”. When limiting to English articles, 122 documents were returned. After removing irrelevant subject areas, e.g. psychology and medicine, and limiting to journal articles only, 48 articles were left for review of title and abstract. We selected 21 articles to review in further detail, and during the search we discovered other relevant articles which are also included in the literature presentation below.

A DAR-service is a rideshare service, where passengers request transportation from a specified origin to a specified destination, possibly also including a time window for their pickup and/or delivery. The DARP considers the design of an optimal route scheme for a fleet of vehicles to serve these requests, with the aim of minimizing transportation costs with respect to vehicle operational costs, passenger inconvenience costs or a combination of these. Thus, the DARP can be considered a special case of the well-studied pickup and delivery problem (PDVRP), which also examines passenger inconvenience ((Cordeau and Laporte, 2007) and (Häll et al., 2012)). The report by Wilson et al. (1976) presents some of the earliest work regarding the DARP, and since then, the literature has continued to investigate various aspects of the problem. Note that the DAR literature often refers to passenger *ride time*, which is equal to what is defined as *transit time* in this thesis.

Wilson et al. (1976) classified a DAR-service into four categories: immediate "standard" service, immediate transferring service, advance pickup service and advance delivery service. The C-DAR-FS will be based on the case of immediate "standard" service, where passengers request the service "at the time they want the service, thereby desiring to be picked up and delivered as soon as possible". The classification has evolved, and today the DARP is often classified into four categories which depends on the ability to modify decisions in response to new information, and to the certainty of the information at the time of decision (Ho et al., 2018). By this classification framework, the C-DAR-FS concerns a *dynamic* and *deterministic* DARP, where requests must be addressed as they occur and all parameters are known with certainty. Note that the C-DAR-FS assigns each request one by one in a chronological order, without considering information regarding future requests. This is similar to the on-line dial-a-ride problem presented by Christman et al. (2018), however, they consider an objective of maximizing revenue, and each vehicle can only service a single request at a time.

The DARP objective often aims to minimize passenger dissatisfaction (e.g. transit times) and/or operational costs (e.g. vehicle tour length). On the one hand, when considering passenger dissatisfaction, the aim is to minimize passenger inconvenience, which could be represented through waiting and transit times (Nasri and Bouziri, 2017), deviations from desired pickup and delivery time windows (Wilson et al., 1976) or maximizing the number of met requests (Reinhardt et al., 2013). It could also be a combination of these measures, as seen in the article by Coslovich et al. (2006). On the other hand, operational costs are considered in Horn (2002) through reduction of route lengths. These problems often consider service quality through the temporal constraints, not explicitly in the objective.

On a final note regarding the objective, the DARP may also be formulated as a multi-objective, which leads to the use of multi-objective methods, including identification of the Pareto optimal frontier (Zidi et al., 2012). These problems often aim to combine an economic and a service quality criterion. Mauri et al. (2009) model an extensive objective with respect to total distance traveled by the vehicles, number of vehicles required, total time of routes, total transit time and total waiting time. Moreover, they relax some of the hard constraints by minimizing violations e.g. with respect to vehicle capacity. Madsen et al. (1995) and Häll et al. (2015) also discuss a mixture of objectives, which considers both operational costs and passenger dissatisfaction. Therefore, the DARP may be modeled with several different objectives.

The DARP often includes hard constraints on waiting, transit and total service times for each passenger to ensure a certain level of service quality is obtained. Thus, the request is considered unmet if not serviced within those given limits. Most commonly, both the pickup and delivery of a request is associated with an earliest and latest time of service (e.g. (Mauri et al., 2009), (Xiang et al., 2008), (Coslovich et al., 2006) and (Madsen et al., 1995)). Moreover, Häll et al. (2012) formulate maximum transit time constraints which are proportional to the direct transit time, and this concept is extended to maximum service times which are utilized in the C-DAR-FS. These time windows can also be defined through maximum delay constraints (Santos and Xavier, 2015). The hard constraints reduce the complexity of the problem when tightened (Häll et al., 2009). However, Quadrifoglio et al. (2008) found that increasing the time-window size by only a few minutes leads to a significant reduction in the required number of vehicles. Thus, identifying fair time windows with respect to customer service and problem complexity can be challenging.

Several extensions to the dynamic DARP have been suggested, which can improve the performance of the system. The two most common concern *regret* and *reshuffling* in which the option to change the assignment of a request is considered. Thus, a request may at first be accepted and receive a pickup time, but after discovering other requests over time, the initial request may be reassigned to another vehicle, receive a new pickup time or even be declined. Such methods are discussed by Häll and Peterson (2013), Fu (2002) and Horn (2002). Another extension concerns unexpected passengers which is discussed by Coslovich et al. (2006). They develop an insertion algorithm for the dynamic DARP where customers may appear at a bus stop without notice, and the bus driver has to immediately consider whether the new request can be accepted or not, based on a feasible delivery insertion.

DARP often concerns a large number of requests, and therefore heuristic solution methods are applied to compute solutions within reasonable time (Reinhardt et al., 2013). Masmoudi et al. (2016) present three heuristic solution methods for the static DARP; one based on Adaptive Large Neighborhood Search (ALNS), and the two others based on a Hybrid Bees Algorithm (BA). Santos and Xavier (2015) solve the dynamic DARP by splitting the day into time periods, where each time period is solved as a static problem with a GRASP heuristic. Muñoz-Carpintero et al. (2015) develop an evolutionary algorithm to solve the dynamic pickup and delivery problem for a DAR-service, and they consider different configurations of particle swarm optimization and genetic algorithms. Mauri et al. (2009) develop a simulated annealing algorithm combined with other heuristics to solve their version of the static multi-objective DARP.

The Integrated Dial-a-Ride problem (IDARP) is a special case of the DARP which models a transportation network with a fixed, scheduled service and a Dial-a-Ride (DAR) service. The aim is to find the optimal route for a request by evaluating both transportation options, and/or a combination of these. The IDARP objective often builds on the ideas from DARP, along with an integration with the fixed schedule. Operational costs are considered in Liaw et al. (1996), Posada et al. (2017), Hickman and Blume (2001) and Häll et al. (2009) through reduction of route lengths, and a bi-objective approach may also be used, which is seen in e.g. Amor et al. (2019), Edwards et al. (2011). Most commonly, time windows are also implemented, like in DARP, and all of the above mentioned IDARP articles, except Edwards et al. (2011), include time windows to ensure a certain level of customer service.

Even though this literature may seem very relevant to the C-DAR-FS, the IDARP differs with respect to allowing transfers, and thus the focus is often shifted to modeling the perfect timing of the transfer between the two services, which is irrelevant in the C-DAR-FS. Furthermore, in IDARP, the DAR-service is most commonly used as a ”last-mile” service connected to the fixed service instead of as a supplement to the the fixed service, because the problem often models the transport of elderly or disabled who cannot access the fixed schedule stops by themselves ((Posada et al., 2017), (Häll et al., 2009), (Hickman and Blume, 2001) and (Liaw et al., 1996)). It also concerns the use of vehicles and road networks, which increases the number of possible pickup and delivery locations. The C-DAR-FS on the other hand, models ferries in an open fjord with specified ports, which supports the need for a transportation system without transfer and last-mile service.

The DARP can be solved or evaluated through simulation processes. Campbell et al. (2016) solve the DARP through an agent-based simulation where each vehicle bids on the request. Häll et al. (2012) present a framework for simulating DAR-services, which may be applied to evaluate the performance of dynamic DARP models. Another simulation framework by Fu (2002) evaluates the effects of automatic vehicle location systems for DAR-services. Furthermore, Shinoda et al. (2003) simulate a fixed schedule and a DAR-service for a given fleet size, where all vehicles are either allocated to one service or the other. They find that ”the usability of the dial-a-ride system degrades quickly when the number of demands increases”. We will extend this concept in the C-DAR-FS by evaluating different allocations of ferries between the fixed schedule and the DAR-service.

9.2 Simulation and Optimization

The C-DAR-FS will be evaluated by a simulation system which contains a kind of optimization procedure when assigning requests to the two ferry services. Therefore, we now continue by an attempt to classify this system by the simulation optimization categories often seen in the literature. As the generation of a fixed schedule will occur only once before the simulation, it is not considered when classifying the simulation system.

Figueira and Almada-Lobo (2014) present a thorough taxonomy of simulation optimization structures, and construct a classification system which is primarily based on the simulation purpose and hierarchical structure between the simulation and optimization. By mapping the purpose and hierarchy, they propose twelve categories, in which they place simulation methods seen in the literature. The simulation system constructed to evaluate the C-DAR-FS can be classified as an *Iterative Optimization-based Simulation* (IOS) which is the interaction between *Solution Generation* (SG) and *Simulation with Optimization-based Iterations* (SOI), according to the classification system provided by Figueira and Almada-Lobo (2014). During the simulation process, a trigger event calls for the optimization procedure, which temporarily halts the simulation to solve an analytical problem based on the system's current state. The output of the optimization model is then used in the simulation, and the process is repeated iteratively. In our simulation system the trigger event is the occurrence of a new request, which calls to the optimization procedure, i.e. the request assignment procedure.

Furthermore, Amaran et al. (2016) present an overview of terminology of optimization problems and classifies the techniques that are usually suitable for different types of problems. According to this categorization, the C-DAR-FS has uncertainty present through unknown requests, and the problem structure is rather complex. Thus, simulation optimization is a common technique to evaluate the problem. In future research, algebraic models may be formulated for the C-DAR-FS which enables the use of stochastic programming and/or robust optimization. In addition, Amaran et al. (2016) discuss discrete-event simulations or systems of stochastic nonlinear and/or differential equations as application areas for simulation optimization techniques. Our simulation system is based on a discrete-event simulation.

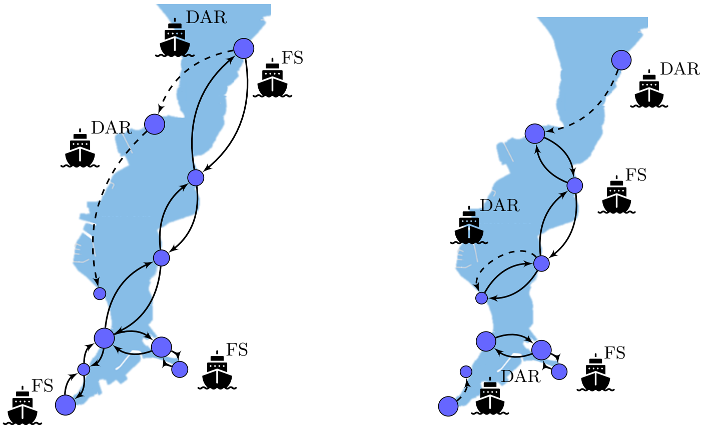
Chapter 10

Problem Description II

This chapter describes the Combined Dial-a-Ride and Fixed Schedule for a Ferry Service (C-DAR-FS) problem in further detail. Firstly, we provide a holistic description of the problem. Next, in Section 10.1, we present the simulation system used to evaluate the C-DAR-FS, and in Section 10.2 we elaborate on the request assignment procedure used within the simulation system.

C-DAR-FS is based on the assumption that two different services exist; a fixed ferry service schedule (*FS*) with given routes and departure frequencies, and a dial-a-ride (*DAR*) service which routes ferries based on realized demand. We denote ferries allocated to the FS-service and to the DAR-service as *FS-ferries* and *DAR-ferries*, respectively. A limited fleet size is available, which is to be allocated between the two services. The overall aim of the C-DAR-FS is to identify the optimal fleet allocation between the FS- and DAR-service, such that the number of serviced requests within a given service level is maximized, while the time spent in the system for each serviced passenger is minimized. The concept of *service level* is quantified by imposing requirements on how long passengers can wait to be picked up and how long it can take before they are delivered. Figure 10.1 visualizes how a ferry system consisting of five ferries may look like with two different ferry allocations. Note that the fixed schedule routes depend on the number of allocated FS-ferries, and that the DAR-ferries have no predetermined route and may travel freely around the fjord to serve demand. In our thesis, we use the solutions of the FSNDP from Part I to generate fixed schedule departures.

As in Part I, we consider a given set of ports, from which all demand occurs. Moreover, all ferries can serve all ports, but the fixed schedule does not necessarily have routes serving all OD-pairs. In addition, the fleet of ferries is assumed to be homogeneous, i.e. they have the same capacity, speed and berthing time. We assume berthing time is static, and thus independent of the number of passengers, the ferry, and the attributes of the port. Furthermore, customers can not withdraw their request or reject a transportation offer. Lastly, besides the request occurrences, we assume deterministic conditions.



(a) Three FS-ferries and two DAR-ferries.

(b) Two FS-ferries and three DAR-ferries.

Figure 10.1: Illustration of two allocations of the C-DAR-FS with a fleet size of five ferries. The solid line indicates a specific route operated by the fixed schedule service, whereas the DAR-ferries have no prespecified route. The dotted lines represent the path which the respective DAR-ferry is currently traveling for illustrative purposes. Source of ferry icon: ”Boat” icon by IconMark, from thenounproject.com.

To evaluate the ferry service with specific ferry allocations in the C-DAR-FS, we construct a simulation system. The relations between the C-DAR-FS and the simulation system is visualized in Figure 10.2. In the simulation system, as in real life, passenger requests occur dynamically over the course of time, and each request is either accepted or rejected as it is received. To solve the problem of assigning a request, we propose a request assignment procedure, which includes an insertion heuristic for the DAR-service.

10.1 Simulation System

In this section, we elaborate on the simulation system used to evaluate given allocations of the C-DAR-FS. We construct an event-based simulation where each event represents a *request*. During the time horizon considered, requests for the ferry service appear over the course of time, and each time a request appears, the simulation performs an assignment procedure to identify the best assignment of that request. This procedure is described in Section 10.2.

The requests are OD-pair specific and contain a number of passengers, i.e. each request i consists of a group of passengers who want to travel from a given origin port to a given destination port. Moreover, each request has a *call-in time*, $t_i^{call-in}$, which is the time the request is placed, and thus appears in the system (Häll et al.,

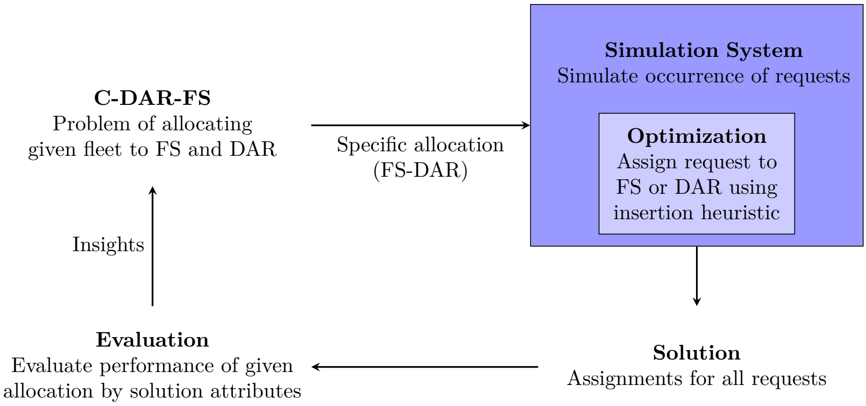


Figure 10.2: Overview of the relations between the C-DAR-FS and the simulation system.

2012). The request occurrences are modeled as OD-pair specific Poisson processes, implying that the time between the requests is exponentially distributed. The number of passengers per request is drawn from a uniform distribution, which is equal for all OD-pairs. In sum, OD-pairs with high demand will have shorter time between the occurrence of new requests than OD-pairs with lower demand, but the average number of passengers per request will be equal.

The simulation system is visualized by a flowchart in Figure 10.3. The *input* consists of a number of parameters: a fixed schedule with times of departure and corresponding routes, direct sailing times between all ports, a given allocation of the fleet between the two services, initial ferry positions for the DAR-service, demand distributions, and a simulation time horizon. Note that the fixed schedule departures are considered given and fixed, thus they will not be changed during the optimization procedure. The *initialize* phase places the DAR-ferries in their respective depots and samples requests in ascending order by their call-in time, within the time horizon considered.

In the simulation system, the requests are assigned consecutively, without any considerations for the future requests. The already assigned requests are implicitly considered, because constraints regarding service quality are imposed. As in the modeling of the FSNDP, there is no option to transfer, i.e. each request must be served with a single ferry. Moreover, all passengers belonging to the same request must travel together on the same ferry service. When a request has been assigned to a ferry, it is not possible to regret that decision, even though another assignment may be more desirable at a later time in the simulation.

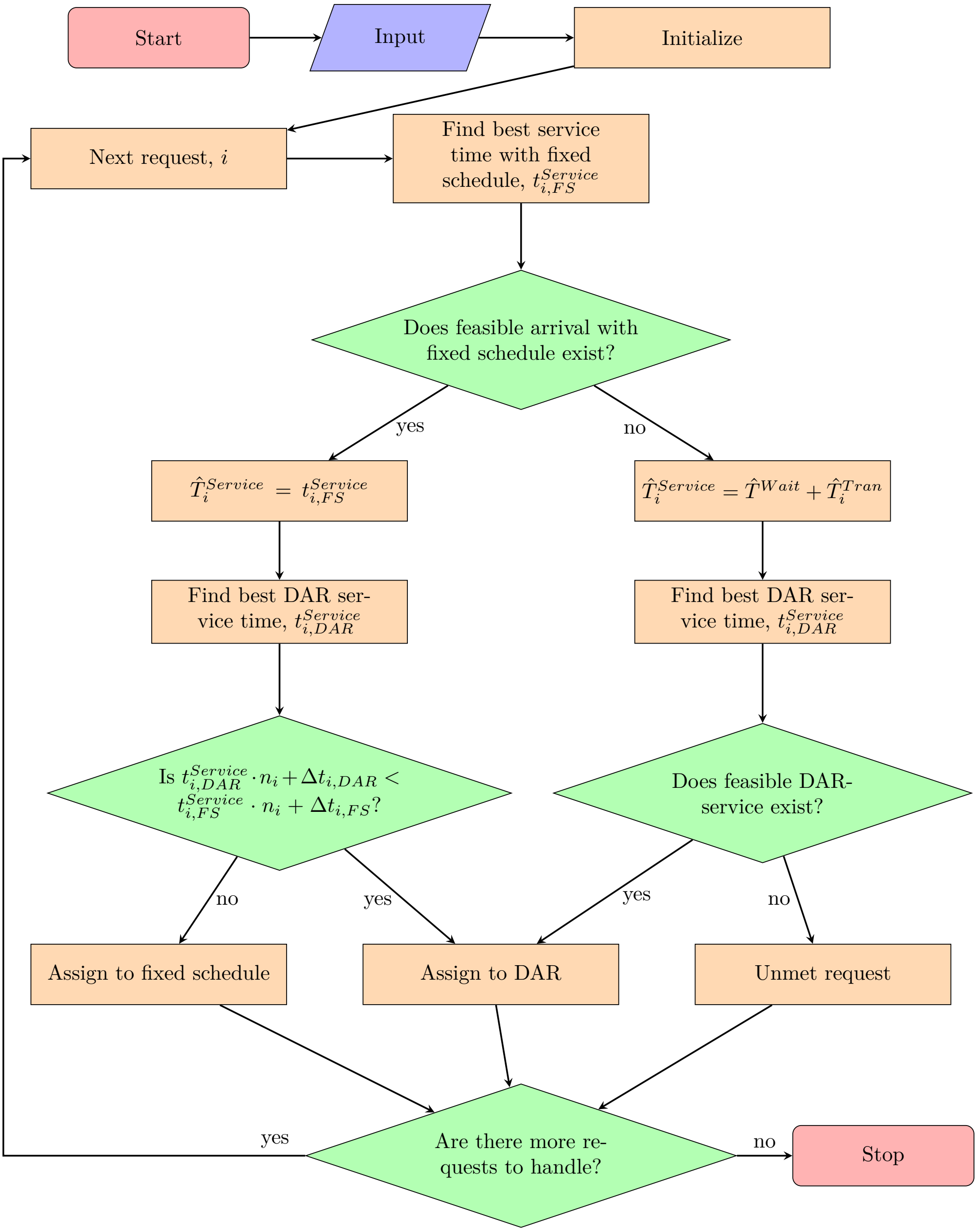


Figure 10.3: Flowchart of the simulation system.

10.2 Request Assignment Procedure

For each request i, we solve the problem of assigning it to a ferry by identifying the best assignment using the fixed schedule and the best assignment using the DAR-service. Afterward we compare these two assignments and fix the request onto the service and ferry associated with the best assignment. The two assignment procedures are based on the same objective and constraints, which are described in Subsection 10.2.1. The procedure of identifying the best service time when assigning i to the fixed schedule, $t_{i,FS}^{Service}$, is elaborated in Subsection 10.2.2. The procedure of identifying the best service time when assigning i to the DAR-service, $t_{i,DAR}^{Service}$, is more comprehensive, because the routes of the DAR-ferries are constructed underway. Thus, we develop an insertion heuristic, which is elaborated in Chapter 11.

10.2.1 Objective and Constraints

The aim of the C-DAR-FS is to maximize the number of met requests within the given service requirements. For each request, a secondary objective is formulated, which is to minimize the total *service time* of the request, i.e the sum of waiting time in the pickup port and transit time to the delivery port for all passengers of the request. We assume all passengers always desire to travel to their destination as fast as possible after the call-in time, implying that the earliest pickup time is the call-in time. Each request in consideration is serviced according to two aspects. In the first aspect, the passengers of the request in consideration are transported to their destination as soon as possible after call-in time. In the second aspect, the passengers already on board the ferry are considered by evaluating the extra service time inflicted by the request in consideration. We select the assignment which minimizes the total impact on service time for all passengers. This is formalized in the following.

We define an *assignment* of a request as a specific combination of a pickup and delivery of the request with a specific ferry. For a request i, let $\mathcal{A}_i$ be the set of all feasible assignments for all ferries $v \in \mathcal{V} = \mathcal{V}^{FS} \cup \mathcal{V}^{DAR}$, i.e. $\mathcal{A}_i = \mathcal{A}_i^{FS} \cup \mathcal{A}_i^{DAR}$. Let n_i be the number of passengers of request i. Moreover, let $t_{ia}^{Service}$ be the service time of request i given assignment $a \in \mathcal{A}_i$, and let Δt_a be the total extra service time incurred for all the passengers already assigned to the ferry associated with assignment a, if assignment a is actually inserted. For each request i the objective is then as described in Equation 10.1.

$$min_{a \in \mathcal{A}_i}\{t_{ia}^{Service} \cdot n_i + \Delta t_a\} \tag{10.1}$$

If the request is assigned to the fixed schedule, no extra service time will incur for the passengers already assigned to that ferry. Although the system does not consider future requests, we will investigate the effects of attempting to free capacity for future requests which may benefit more from the use of the DAR-ferries. Thus, we introduce a threshold value, Δ^{Thres}, such that a request only will be assigned to a DAR-ferry if it is sufficiently better than the fixed schedule, with respect to service time. When evaluating Equation 10.1, Δt_a for an assignment to the fixed schedule will be the negative of this threshold value times the number of passengers in the request. Thus, the Δt_a for a fixed schedule assignment, $\Delta t_{i,FS}$, is given by $\Delta t_{i,FS} = -\Delta^{Thres} \cdot n_i$, where i is the request in consideration. This concept implies that the DAR-service must deliver each passenger of the request in consideration at least Δ^{Thres} faster than the fixed schedule service, and also compensating for the extra service time incurred for the passengers already on board.

Constraints

We impose two requirements related to the service quality of the ferry service. The first is a *maximum waiting time*, $\hat{T}^{Wait}$, which is the maximum time between the call-in time of a request and the time the passengers are picked up. The second is a *maximum service time* of the request i, $\hat{T}_i^{Service}$, which is the sum of the maximum waiting time, and the maximum transit time, $\hat{T}_i^{Tran}$. As in Part I, the maximum transit time is proportional to the direct transit time, and it is given by $\hat{T}_i^{Tran} = (1 + Q^{Max}) \cdot T_{od}^{Direct}$, where o and d denotes the origin and destination of the request, respectively. Note however, that there is no constraint directly linked to the maximum transit time in the C-DAR-FS. As long as the service time is below the maximum service time, the transit time can be higher than $\hat{T}_i^{Tran}$. This is because we assume that the passengers always will prefer an earlier arrival rather than shorter transit time on the ferry. Thus, if the waiting time is very low, longer transit times can occur on the DAR-ferry. However, a feasible assignment to the fixed schedule will not have transit times exceeding $\hat{T}_i^{Tran}$, because we utilize parameter **A** from Part I to identify feasible routes. Let the waiting time of request i with assignment a be t_{ia}^{Wait}. The service quality constraints can then be formulated as in Constraint 10.2 and Constraint 10.3.

$$t_{ia}^{Service} \leq \hat{T}_i^{Service} \tag{10.2}$$

$$t_{ia}^{Wait} \leq \hat{T}^{Wait} \tag{10.3}$$

The service quality constraints, together with the assumption that the passengers want to travel as soon as possible after call-in, form the feasible time windows for the insertions of pickup and delivery of a request i. Corresponding to the notation commonly used in DAR literature (Häll et al., 2012), the earliest pickup time (EPT) is given by the call-in time of i, and latest pickup time (LPT) is restricted by the maximum waiting time, $\hat{T}^{Wait}$. The earliest delivery time (EDT) is simply the pickup time plus direct sailing time between pickup and delivery. The latest delivery time (LDT) is given by the maximum service time, $\hat{T}_i^{Service}$. A visualization of the time windows is given Figure 10.4.

Moreover, we want to ensure that all passengers are guaranteed to be serviced at least as fast as they would have with the fixed schedule. Thus, if there exists a

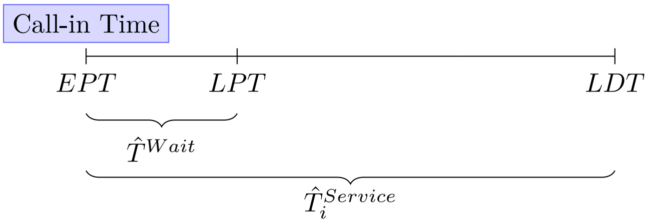


Figure 10.4: A visualization of the feasible time windows for pickup and delivery of request i, with earliest pickup time (EPT), latest pickup time (LPT), and latest delivery time (LDT).

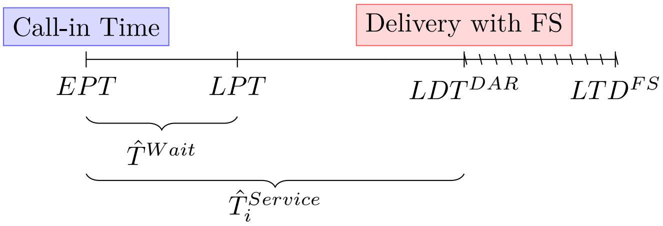


Figure 10.5: A visualization of the feasible time windows for pickup and delivery of request i using the DAR-service when the best assignment with the fixed schedule (FS) is identified. The time windows are marked with the earliest pickup time (EPT), latest pickup time (LPT), and latest delivery time (LDT).

feasible assignment to the fixed schedule, we update the maximum service time constraint for an assignment on the DAR-service to be the service time which the fixed schedule may offer. This is visualized in Figure 10.5. If other requests are assigned to the ferry at a later point in time, the arrival may be postponed, but not more than the arrival of the fixed schedule service. In addition, this updated maximum service time for the DAR-ferries may reduce computational time required by pruning insertions which would not have been selected anyway due to the objective of minimizing service time.

Lastly, we impose capacity constraints for the ferries. Recall that in Part I the FSNDP is solved without capacity constraints. However, in the C-DAR-FS, when assigning passengers on either an FS-ferry or a DAR-ferry, capacity constraints are imposed on the ferries of both service types. We denote the capacity of a ferry as N^{Max}. Let $\mathcal{Y}_a$ be the set of visits to ports for the ferry associated with a *in between* the pickup and delivery of request i with assignment a. Further, let l_y be the number of passengers on board the ferry when departing from $y \in \mathcal{Y}_a$. Moreover, let l_{i^+} be the number of passengers on board prior to pickup of request i. Assignment a can not violate the capacity of the ferry at any point between the request pickup and delivery, also considering the other requests already assigned to the ferry. Therefore, we have that the constraints formulated in Constraint 10.4

and Constraints 10.5 must hold.

$$l_{i^+} + n_i \leq N^{Max} \tag{10.4}$$

$$l_y + n_i \leq N^{Max}, \quad y \in \mathcal{Y}_a \tag{10.5}$$

If a feasible assignment is identified on both service types, the best one according to the objective is chosen, and the assignment of the request is fixed. Then, let t_i^{Wait} and $t_i^{Service}$ be the waiting time and service time of request i, respectively, and update their values according to the best assignment. Note that, even though there is no option to regret an assignment of a request on a ferry, the waiting time and delivery time of a request can change when another request is assigned to the same DAR-ferry, due to a change in the routing of the ferry. However, when assigning a new request to a ferry, the constraints regarding maximum waiting time and maximum service time must still hold for the requests which are already assigned. If neither the fixed ferry schedule nor the DAR-service are able to serve the request within the two service quality constraints or without violating the capacity constraints, the request is rejected and thus considered *unmet.*

10.2.2 Assignment of a Request to the Fixed Schedule

We now continue by presenting the assignment procedure for the FS-service. First, we elaborate on the process of finding the best feasible assignment for the request in consideration. Subsequently, we present the steps required to assign the request to an FS-ferry, if this assignment has been deemed the best for the entire ferry system.

Identification of the Best Assignment

For request i, it must be checked whether there exists a feasible assignment $a \in \mathcal{A}_i^{FS}$ of request i on one of the FS-ferries $v \in \mathcal{V}^{FS}$, and if so, the best one must be identified.

For a given FS-ferry $v \in \mathcal{V}^{FS}$, we define the set $\mathcal{A}_{iv}^{FS} \subseteq \mathcal{A}_i^{FS}$ as the set of feasible assignments on ferry v. Each assignment contains information relating to a specific departure from the pickup port and arrival in the delivery port. From this, we can calculate the corresponding waiting and service time, t_{ia}^{Wait} and $t_{ia}^{Service}$, respectively. A feasible assignment $a \in \mathcal{A}_{iv}^{FS}$ satisfies the service quality and capacity constraints. When allocating a request to the fixed schedule, no passengers of other requests will be affected. Thus, the service quality constraints only concern the passengers of the request in consideration and are formulated as displayed in Constraint 10.2 and Constraint 10.3.

Moreover, a feasible assignment a must not violate the capacity of the ferry at any point between the request pickup and delivery, also considering the other requests already assigned to the FS-ferry. Thus, we have that the constraints formulated in Constraint 10.4 and Constraints 10.5 must hold.

Since we do not prioritize between the FS-ferries, and the assignment of a request to an FS-ferry never affects the passengers of other assigned requests, Δt_a is zero when comparing the FS-assignments. Then, the best feasible assignment to the fixed schedule is simply the one with the shortest service time, as formalized in Equation 10.6. The waiting time associated with this assignment is denoted $t_{i,FS}^{Wait}$.

$$t_{i,FS}^{Service} = min_{a \in \mathcal{A}_i^{FS}} \{ t_{ia}^{Service} \cdot n_i \} \tag{10.6}$$

Later, when comparing with the best DAR-assignment to identify which service to assign the request to, recall that $\Delta t_{i,FS} = -\Delta^{Thres} \cdot n_i$.

Fixation of an Assignment to the FS-Service

As visualized in Figure 10.3, if $t_{i,FS}^{Service} \cdot n_i + \Delta t_{i,FS} \leq t_{i,DAR}^{Service} \cdot n_i + \Delta t_{i,DAR}$, request i is assigned to the fixed schedule. The request is then added to the list of assigned requests, $\mathcal{R}_{v^*}$ for the respective FS-ferry, v^*. The number of passengers on board the ferry after each visit $y \in \mathcal{Y}_{a^*}$ is increased with n_i passengers. Finally, the waiting time and service time of request i is set to $t_i^{Wait} = t_{i,FS}^{Wait}$ and $t_i^{Service} = t_{i,FS}^{Service}$, respectively.

Chapter 11

Dial-a-Ride Insertion Heuristic

This chapter presents the insertion heuristic for the dial-a-ride problem (DARP) in the C-DAR-FS, i.e. the procedure for identifying the best assignment of a request to the DAR-system and the procedure of fixing the assignment of the request to a DAR-ferry. Firstly, we present a flowchart of the insertion heuristic and explain the procedure briefly as a whole. In Section 11.1 we discuss the possible insertions of a request on a given DAR-ferry. Furthermore, in Section 11.2 we elaborate on the procedure of identifying feasible assignments concerning the capacity and service quality constraints. In Section 11.3, we present the procedure to identify the best assignment on the DAR-service, and lastly, in Section 11.4 we discuss how a may be request fixed to a DAR-ferry.

The procedure to find the best assignment of a request i using the DAR-service corresponds to the process displayed in Figure 10.3, which is to "find the best DAR service time ($t_{i,DAR}^{Service}$)", and the process is visualized more detailed in Figure 11.1. The *input* consists a set of DAR-ferries, $\mathcal{V}^{DAR}$, with information about their last visited port and a list of already assigned requests ($\mathcal{R}_v$). Moreover, we have a request i with a pickup port, delivery port, call-in time, and a maximum service time. An *assignment* of request i on a DAR-ferry consists of a pickup insertion, i^+ and a delivery insertion, i^-, and the sets of possible pickup and delivery insertions are denoted $\mathcal{P}_{iv}$ and $\mathcal{D}_{i^+v}$, respectively. The best combination of a pickup and a delivery is the best assignment of request i on a specific ferry, and the best assignment across all DAR-ferries is the output of this insertion heuristic procedure.

11.1 Possible Pickup and Delivery Insertions

A request may be inserted into the route of a DAR-ferry at various positions. Therefore, to check whether the DAR-ferry has any feasible insertions and if so,

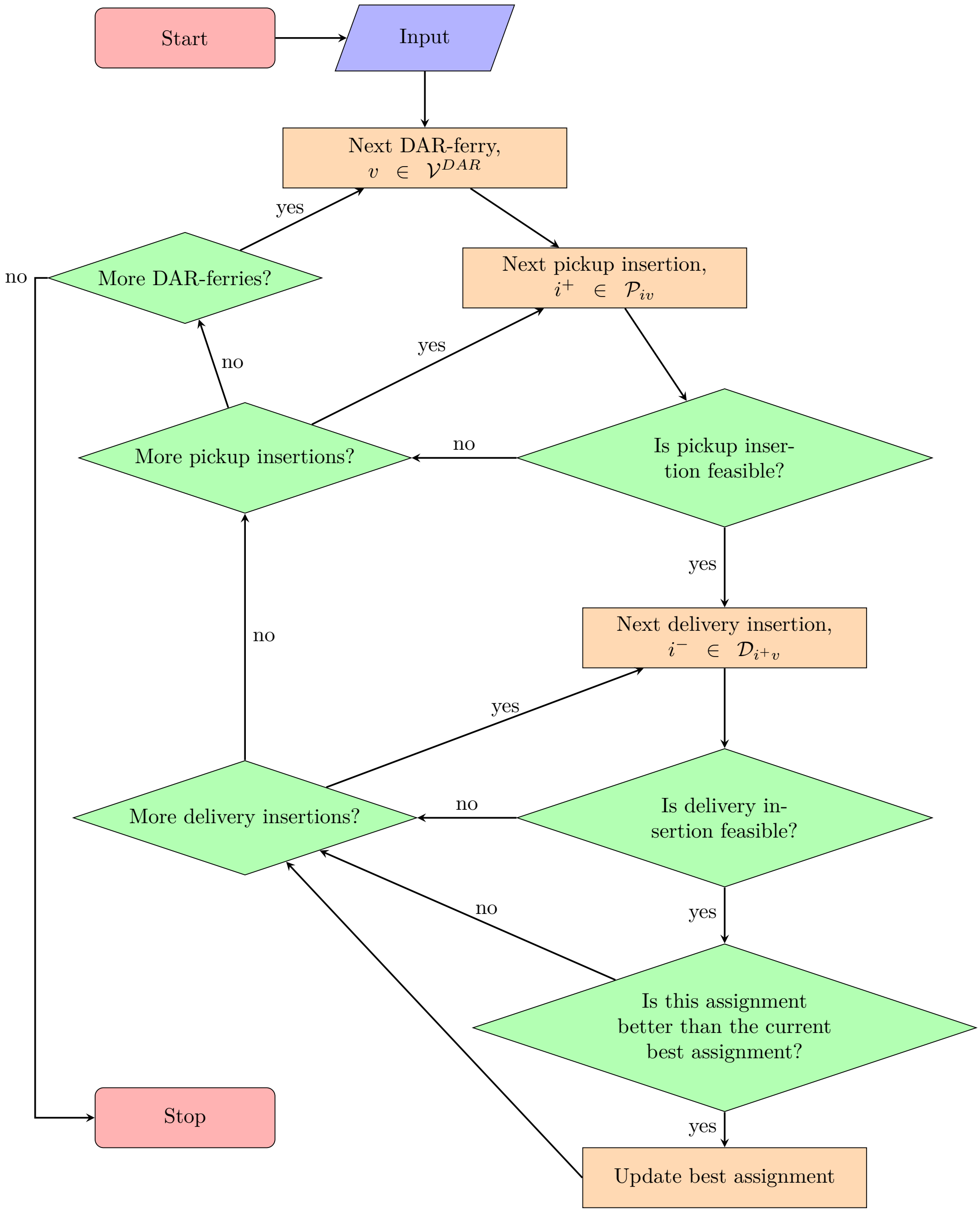


Figure 11.1: Flowchart of the DAR insertion heuristic.

which one is the best, we need to evaluate every insertion option. In the following, we elaborate on how we identify all possible assignments, i.e. all combinations of pickup and delivery insertions of a given request on a specific DAR-ferry.

At call-in time for a request i, $t_i^{call-in}$, a DAR-ferry v will have a list of already assigned requests, $\mathcal{R}_v$. Each request is associated with two port visits, a pickup and a delivery of the passengers. All visits, which are not yet completed at call-in time, form what we denote the ferry's list of *planned visits*, which represents the ferry's projected route. Moreover, the ferry will have a *last visited port*, i.e. the last port the ferry visited before call-in time. Note that at call-in time, the ferry will always have left the last visited port, if it has planned visits.

If the DAR-ferry has no planned visits, we assume it remains in the last visited port until it receives a new request assignment. Thus, the assignment of request i will simply be traveling to the pickup port from the last visited port directly after call-in time, and from there, traveling directly to the delivery port. However, if the ferry has planned visits, both the pickup and the delivery of the request can be placed before all planned visits, somewhere in between the planned visits or after all other planned visits. Recall that for request i, i^+ and i^- denote the pickup and delivery insertion, respectively, and these insertions correspond to port visits, thereby also a specific port. Inspired by Campbell et al. (2016), we have identified seven types of insertion options:

- Case 1: Pickup of request i is inserted right after the last visited port, thus before the first planned visit.
    - Case 1.1: Delivery of request i is also inserted before the first planned visit, i.e. the ferry travels directly between pickup and delivery of the request.
    - Case 1.2: Delivery is inserted somewhere in between the planned visits.
    - Case 1:3: Delivery is inserted after all planned visits.
- Case 2: Pickup of request i is inserted somewhere in between the planned visits.
    - Case 2.1: Delivery of request is directly after pickup.
    - Case 2.2: There is at least one visit between pickup and delivery of the request. Delivery is not after all planned visits.
    - Case 2.3: Delivery is inserted after all planned visits.
- Case 3: Pickup and delivery of request i are inserted after all planned visits.

The different cases are illustrated in Figure 11.2, and they form the set of possible pickup insertions of request i on ferry v, $\mathcal{P}_{iv}$ and the set of possible delivery insertions given pickup i^+, $\mathcal{D}_{i^+v}$. Note that some cases are relatively equal mathematically, but we separate the cases to illustrate the variety of insertion options. As the figure illustrates, for each combination of a pickup and a delivery insertion,

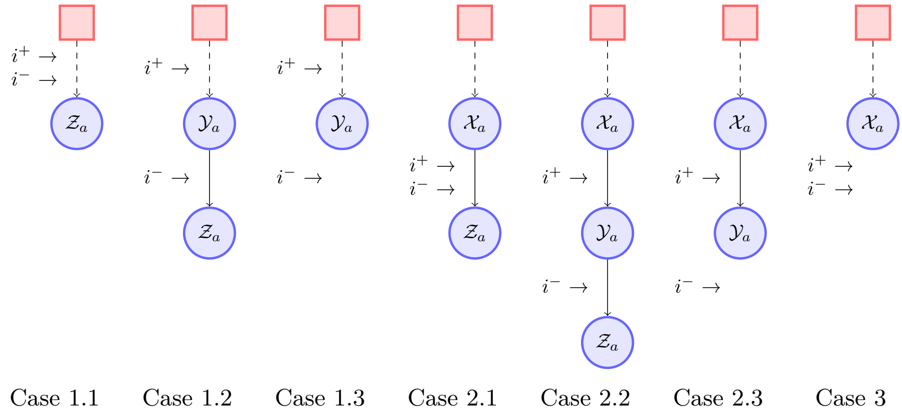


Figure 11.2: Possible insertion cases of a request i into the route of a DAR-ferry. The square node (red) represents the last visited port. The dashed arc indicates that the ferry is on its way from the last visited port. The round nodes (blue) represent one or more planned visits. Possible pickup and delivery insertions of the request are denoted with i^+ and i^-, respectively.

a, we define $\mathcal{X}_a$ as the list of visits before pickup, $\mathcal{Y}_a$ as the list of visits in between pickup and delivery, and $\mathcal{Z}_a$ as the list of visits after delivery of request i. Cases 1.1, 1.2, and 1.3, are an extension to the work of Campbell et al. (2016). With pickup *before* the first planned visit, the ferry has to be redirected in these cases. We elaborate more on the challenges concerning this redirection in the next section.

11.2 Feasibility Check

In this section, we explain how a request assignment on a DAR-ferry is deemed feasible. Since the feasibility relates to capacity and service level, we must calculate the capacity and temporal effects of the insertion on the request itself and on the previously assigned requests. The capacity check is relatively straightforward, but the calculation of waiting and transit times requires further elaboration. Thus, we present the calculations of the waiting and service times in Subsection 11.2.1 before elaborating on the feasibility constraints in Subsection 11.2.2.

11.2.1 Calculation of Waiting and Service Times

The waiting and transit time of a request are directly linked to the time of pickup and delivery, thus we start by presenting their calculation. We identify the delays for the passengers already on board caused by the pickup and delivery insertions, i.e. Δt_a^P and Δt_a^D, by calculating the pickup time, t_{ia}^P and delivery time, t_{ia}^D, of request i. As mentioned in Section 11.1, Case 1.1. Case 1.2, and Case 1.3 require a redirection of the ferry, and thus the calculation of the pickup time, t_{ia}^P, in these cases is presented in the final part of this section. However, by assuming the pickup time is known, we can calculate t^D_{ia}, Δt^P_a, and Δt^D_a the same way for all cases, despite redirection. As mentioned previously, insertions and visits correspond to a specific port, and therefore they may be used to identify transit times.

Let the last port visited before i^+ be g^+, i.e. the last element of the set $\mathcal{X}_a$. The departure time from g^+ is denoted t_{g^+}. If the DAR-ferry has no planned visits, t_{g^+} equals $t^{call-in}_i$. Furthermore, recall from Section 7.2 that the berthing time in a port is T^{Berth}, and the direct sailing time between ports x and y is T^{Direct}_{xy}. Except for in Case 1, we calculate the pickup time as described in Equation 11.1.

$$t^P_{ia} = t_{g^+} + T^{Direct}_{g^+i^+} + T^{Berth} \tag{11.1}$$

Moreover, if the DAR-ferry has planned visits, let the first planned visit *after* i^+ be k^+, i.e. the first element of the set $\mathcal{Y}_a$. The planned departure time from k^+ prior to the pickup insertion is denoted t_{k^+}. We then have that the delay due to the pickup insertion is as formulated in Equation 11.2.

$$\Delta t^P_a = t^P_{ia} + T^{Direct}_{i^+k^+} + T^{Berth} - t_{k^+}. \tag{11.2}$$

When considering the delivery of request i, let the last port visited before i^- be g^-, i.e. the last element of the set $\mathcal{Y}_a$. The departure time from g^- is denoted t_{g^-}. Note that t_{g^-} is the planned departure time from g^- prior to the actual assignment of request i, i.e. the departure time from g^- if neither i^+ nor i^- are inserted. Thus, we calculate the time of delivery as shown in Equation 11.3. We define the passengers as *delivered* as soon as the ferry arrives in i^-, we do therefore not include berthing time in the delivery port when calculating delivery time, t^D_{ia}.

$$t^D_{ia} = \begin{cases} t^P_{ia} + T^{Direct}_{i^+i^-}, & \text{if delivery is directly after pickup,} \\ & \text{i.e. Cases 1.1, 2.1, and 3} \\ t_{g^-} + T^{Direct}_{g^-i^-} + \Delta t^P_a, & \text{otherwise.} \end{cases} \tag{11.3}$$

Furthermore, if the DAR-ferry has planned visits, let the first planned visit *after* i^- be k^-, i.e. the first element of the set $\mathcal{Z}_a$. The planned departure time from k^- prior to the pickup and delivery insertion is denoted t_{k^-}. We then have that the delay caused by the delivery insertion of the request is as displayed in Equation 11.4.

$$\Delta t^D_a = t^D_{ia} + T^{Direct}_{i^-k^-} + T^{Berth} - t_{k^-}. \tag{11.4}$$

The waiting time for request i with assignment a is then calculated as $t^{Wait}_{ia} = t^P_{ia} - t^{call-in}_i$, and the service time of the request is calculated as $t^{Service}_{ia} = t^D_{ia} - t^{call-in}_i$.

For the passengers associated with the already assigned requests $j \in \mathcal{R}_v$ on DAR-ferry v, the assignment of request i can lead to an increase in their respective

Table 11.1: Overview of how an insertion of request i affects the waiting times and transit times of another request j assigned to the same DAR-ferry. The sets $\mathcal{X}_a$, $\mathcal{Y}_a$, and $\mathcal{Z}_a$ denote the lists of visits prior to the pickup of i, in between pickup and delivery of i, and after delivery of i given assignment a, respectively.

	$j^+ \in \mathcal{X}_a$			$j^+ \in \mathcal{Y}_a$		$j^+ \in \mathcal{Z}_a$
	$j^- \in \mathcal{X}_a$	$j^- \in \mathcal{Y}_a$	$j^- \in \mathcal{Z}_a$	$j^- \in \mathcal{Y}_a$	$j^- \in \mathcal{Z}_a$	$j^- \in \mathcal{Z}_a$
$\Delta t_{j,a}^{Wait}$	0	0	0	Δt_a^P	Δt_a^P	Δt_a^D
$\Delta t_{j,a}^{Tran}$	0	Δt_a^P	Δt_a^D	0	$\Delta t_a^D - \Delta t_a^P$	0
$\Delta t_{j,a}^{Service}$	0	Δt_a^P	Δt_a^D	Δt_a^P	Δt_a^D	Δt_a^D

waiting, transit and service times, if it is in fact assigned. We denote the shift in waiting time for request j due to the assignment a of i as $\Delta t_{j,a}^{Wait}$ and the shift in transit times as $\Delta t_{j,a}^{Tran}$. The shift in service time is given as the sum of the shift in waiting and transit time, $\Delta t_{j,a}^{Service} = \Delta t_{j,a}^{Wait} + \Delta t_{j,a}^{Tran}$. These time shifts depend on where the pickup visit, j^+, and the delivery visit, j^- of request j are located in the route of ferry v relative to the pickup and delivery request i. Recall that we denote the list of visits prior to the pickup of i, in between pickup and delivery of i, and after delivery of i as $\mathcal{X}_a$, $\mathcal{Y}_a$, and $\mathcal{Z}_a$, respectively. How the assignment of i affects the passengers associated with the already assigned requests is displayed in Table 11.1.

Calculation of Pickup Time for Case 1

The calculation of the pickup time t_{ia}^P when the pickup is inserted before all planned visits (Case 1) requires some extra consideration, because the insertion requires *instant redirection* of the ferry underway. We know the direct transit time between all ports, but since the system does not consider coordinate information, it is difficult to know the ferry's exact whereabouts at the time of call-in, if it is not waiting or berthing in a port. Thus, the calculation of the pickup time for the request is not trivial. We develop a procedure to calculate an *approximation* of the pickup time for a ferry which is redirected.

We make two key assumptions:

- The time for any calculation is so small that any movement of the ferry during the calculation is negligible.
- From the time the ferry left the last port to the call-in time we assume it has traveled in the *completely wrong way*, the *completely right way* or *not moved* from the last port.

The last assumption indicates a simplified system where the DAR-ferries only move along a two-dimensional axis. For our practical case in the Kiel fjord, the model is based on the assumption that the ferries only travel in the north/south direction, hence disregarding movement in the east/west direction. Thus, the change in *latitude* of the ferry is the only relevant movement. Due to the geographic attributes of the Kiel fjord with long distances in the north/south direction and shorter distances in the east/west direction, the position assumptions seem reasonable in most of the considered cases.

The pickup time in this insertion case depends on the relative position between the DAR-ferry (given by the next planned visit), the last visited port and the request's pickup port. Following the notation introduced previously, let the port of the last finished visit prior to the pickup be denoted g^+, and the time the ferry departed from g^+ be t_{g^+}. Then, we have that the time passed between the last visit and the call-in time is $t_i^{passed} = t_i^{call-in} - t_{g^+}$. Based on the assumptions, we identify four different relative position options and their respective pickup times. An illustration of the four position options is given in Figure 11.3, and they are explained as follows:

I. **The ferry has traveled the wrong way.** This is the case if the next planned visit is located in the opposite direction of the pickup port of the request, e.g. the ferry is heading north, but the request pickup port is located south of the last visited port. The ferry has to turn, and travel back the distance it traversed during the time passed. Pickup time can be calculated as $t_{ia}^P = t_i^{call-in} + T_{g^+i^+}^{Direct} + T^{Berth} + t_i^{passed}$.

II. **The ferry has traveled the right way.** This is the case when the next planned visit and the request pickup port are located in the same direction from the last visited port, e.g they are both located north of the last visited port. If the next planned port is further away than the pickup port of the request, the ferry has not traveled past the pickup port at call-in time. This means that the ferry has already traversed some part of the path to the pickup port. Thus, pickup time can be calculated as $t_{ia}^P = t_i^{call-in} + T_{g^+i^+}^{Direct} + T^{Berth} - t_i^{passed}$.

III. **The ferry has not changed its latitude.** This is the case if the last visited port and the next planned port have the same latitude. Then the ferry has only traveled in the east/west direction, and so the assumption is that the time to pickup is simply the direct transit time between the port of the last finished visit and the pickup port of the request and berthing time, $t_{ia}^P = t_i^{call-in} + T_{g^+i^+}^{Direct} + T^{Berth}$.

IV. **The ferry has traveled the right way, but past the request pickup port.** This is the case when both the next planned port and the pickup port of the request are located in the same direction from the last visited port, but the next planned port is further away, and at call-in time, the ferry is already past the request pickup port, so it has to turn. The pickup time can then be calculated as $t_{ia}^P = t_i^{call-in} - T_{g^+i^+}^{Direct} + T^{Berth} + t_i^{passed}$.

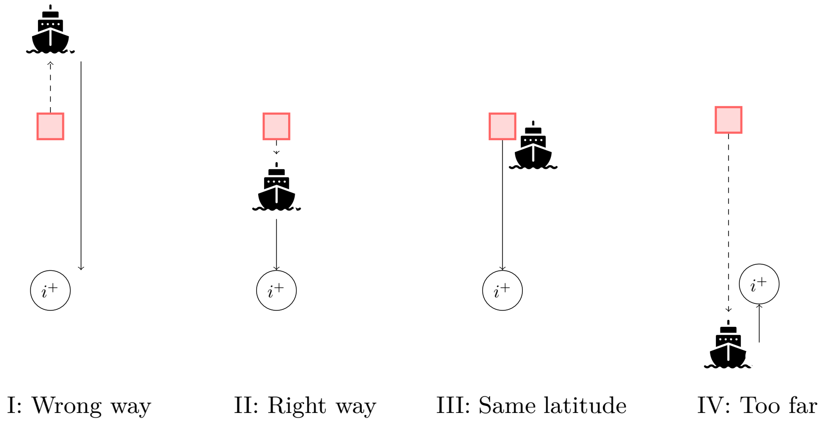


Figure 11.3: Illustration of possible positions of the DAR-ferry at call-in time. The red square denotes the ferry's last visited port, while i^+ denotes the pickup port of the request. The dotted line illustrates the distance traversed by the ferry from the last visit until call-in time. The solid line illustrates the approximated distance to the pickup port after call-in time. Source of ferry icon: "Boat" icon by IconMark, from thenounproject.com.

11.2.2 Feasibility Constraints

For assignment $a \in \mathcal{A}_{iv}^{DAR}$ of request i on a DAR-ferry $v \in \mathcal{V}^{DAR}$ to be feasible, it must not violate the service quality constraints both regarding the passengers of request i and the passengers associated with the already assigned requests $j \in \mathcal{R}_v$. Hence, we have that for a to be feasible Constraint 10.2 and Constraint 10.3 must hold, along with Constraints 11.5 and Constraints 11.6.

$$\Delta t_{j,a}^{Service} + t_j^{Service} \leq \hat{T}_j^{Service}, \quad j \in \mathcal{R}_v \tag{11.5}$$

$$\Delta t_{j,a}^{Wait} + t_j^{Wait} \leq \hat{T}^{Wait}, \quad j \in \mathcal{R}_v \tag{11.6}$$

Moreover, as for the FS-ferries described in Subsection 10.2.2, the feasibility relating to capacity must be checked. Pickup of the new passengers must neither exceed the capacity with respect to the passengers already on board, nor the passengers that are planned to be picked up at any visit between the pickup and delivery of the request. Thus, Constraint 10.4 and Constraints 10.5 must hold for assignment a on the DAR-ferry.

11.3 Identification of the Best Assignment

To evaluate whether a feasible assignment of a request on a DAR-ferry is the best one, we apply the objective presented in Equation 10.1. Let $\mathcal{A}_i^{DAR}$ be the set of feasible insertion combinations of pickup and delivery, i.e. assignments, for request i across all DAR-ferries. The first part of the objective relates to the request in consideration. The second part concerns the passengers associated with already assigned requests, i.e. passengers which are already on board or planned to be picked up. For a given $a \in \mathcal{A}_i^{DAR}$, let the number of passengers in the already assigned requests, which is to be delivered *in between* the pickup and delivery of request i, be denoted as $n_a^{\mathcal{Y}}$. As stated in Table 11.1, each of these passengers incur an extra time of Δt_a^P, because only the pickup of the request in consideration affects their service time. Moreover, let the number of passengers in the already assigned requests, which is to be delivered *after* the delivery of the request in consideration, be denoted $n_a^{\mathcal{Z}}$. Here, every passenger incurs an extra time of Δt_a^D according to Table 11.1, because the delivery of the request in consideration also affects their service time. Since we do not prioritize between the DAR-ferries, this evaluation does not contain a threshold. Hence, we have that Δt_a for the DAR-service, which we denote, $\Delta t_{i,DAR}$, is given by $\Delta t_{i,DAR} = \Delta t_a^P \cdot n_a^{\mathcal{Y}} + \Delta t_a^D \cdot n_a^{\mathcal{Z}}$, and the best assignment of request i on the DAR-service is identified by Equation 11.7.

$$t_{i,DAR}^{Service} = min_{a \in \mathcal{A}_i^{DAR}} \{ t_{ia}^{Service} \cdot n_i + \Delta t_a^P \cdot n_a^{\mathcal{Y}} + \Delta t_a^D \cdot n_a^{\mathcal{Z}} \} \tag{11.7}$$

When this process is completed, we have identified the best service time across all DAR-ferries along with the corresponding assignment. Thus, we can proceed by comparing this assignment to the fixed schedule as discussed in Chapter 10.

11.4 Fixation of an Assignment to the DAR-Service

As visualized in Figure 10.3, if $t_{i,DAR}^{Service} \cdot n_i + \Delta t_{i,DAR} < t_{i,FS}^{Service} \cdot n_i + \Delta t_{i,FS}$, request i is assigned to the DAR-service.

When a request is assigned to a DAR-ferry, $v*$, the request is added to the list of assigned requests, $\mathcal{R}_{v*}$. The waiting times and transit times of the already assigned requests are updated by adding the shifts in time as described in Table 11.1. The pickup and delivery of request i is added to the list of planned visits, and the departure and delivery times of the other visits are updated. Moreover, as when assigning a request to an FS-ferry, the number of passengers on board the ferry after each visit $y \in \mathcal{Y}_a$, l_y is increased with n_i passengers.

Lastly, if the DAR-service provides the best assignment according to the objective, $t_i^{Service}$ is set to $t_{i,DAR}^{Service}$, and t_i^{Wait} is set to the corresponding waiting time.

Chapter 12

Computational Study II

The C-DAR-FS has been implemented and tested for various test instances, and the following chapter presents the results. Initially, we construct the test instances in Section 12.1. Subsequently, we present the results and conduct analyses of the solutions in Section 12.2. Lastly, we provide managerial insights in Section 12.3. The simulation system and insertion heuristic are written in Python 3.7 and test instances for the C-DAR-FS have been computed on a Lenovo M5 with two Intel E5-2643v3 processors, delivering a CPU of 3.4 GHz and 512 GB RAM.

12.1 Test Instances and Implementation

The test instances are based on the *full* port case as described in Section 7.1. Furthermore, we define some additional parameters which are relevant for the simulation. Firstly, each ferry has a capacity, N^{Max}, of 100 passengers. This capacity is selected, because the Kiel Tug and Ferry Company (SFK) plans to construct a purely electrically powered 100-passenger ferry, which will be serving Ferry line 2 from 2021 (Pankratz and Müller-Lupp, 2020*b*). Secondly, the maximum waiting time for a passenger, $\hat{T}^{Wait}$ is set to 30 minutes, because it seems reasonable with respect to customer service. Thirdly, the size of each request, n_i, is sampled from a uniform distribution between one and six. An overview of the parameters can be seen in Table 12.1. Lastly, the simulation time horizon is set to 400 hours. We tested the convergence rate for a selected test instance, and the percentage of met requests converges before 50 hours within a few minutes of computational time. However, we simulate for a longer time horizon to reduce the risk of non-convergence when simulating other test instances.

Since the C-DAR-FS aims to model the interaction between a fixed schedule and a DAR-service, we require information about both services. We choose to solve the FSNDP presented in Part I to generate fixed schedules with the given number of allocated FS-ferries. Thus, the relevant parameters remain as described in Chapter 7,

Table 12.1: Numerical values of the constant parameters used when evaluating the C-DAR-FS.

Parameter	**Symbol**	**Values**
Ferry capacity	N^{Max}	100 $passengers$
Maximum waiting time	$\hat{T}^{Wait}$	30 $minutes$
Size of request i	n_i	[1, 6] $passengers$

and we emphasize that the maximum excess transit time is still $Q^{Max} = 100\%$. In addition, the FSNDP is solved for the average sample of demand and $R^{Max} = 6$ for all tests in Part II. The solution of the FSNDP contains a set of services, where each service consists of a route, a departure frequency and a port and port call in which the waiting time between departures occurs, i.e. the waiting port. To convert this information to an actual departure schedule, we choose the waiting port to be the start port of the route. If the solution contains several services with the same frequency and the same start port, the departures from the start port are spread evenly over the hour across the routes. For example, if two different routes with frequency of three has Laboe as their start port, one of the routes will have departure from Laboe at -:00, -:20 and -:40, while the other one will depart from Laboe at -:10, -:30, and -:50. The routes always have the same departure times every hour, and thereby the departure schedule is created. The departures from the other ports are found by use of the transit times from Subsection 7.2.1. The routes of the DAR-ferries are constructed iteratively during the simulation. At the start of the simulation, to spread the DAR-ferries across the fjord, they start at different ports. These starting ports are determined based on their size, where large ports are prioritized.

Following the presentation of the constant parameters, we now elaborate on the varying parameters of the test instances, which are cases related to the fleet size and allocation of the ferries, the demand, the threshold value, the minimum required frequencies, and the included ports for the FSNDP.

Firstly, we consider total fleet sizes up to 30 ferries, where each ferry is either allocated to the fixed schedule (FS), or the DAR-service (DAR). We test all fleet allocation combinations for all considered fleet sizes. Secondly, we consider three demand cases, which we denote *low*, *regular* and *high*. These three cases are based on the demand presented in Part I, but have been reduced by a factor of 18, 6 and 2, respectively, due to the original demand yielding unrealistically high numbers of passengers in the system. The resulting *low* demand represents a reasonable estimate to the current peak-hour demand in the Kiel fjord, whereas the *regular* and *high* demand represent three and nine times this demand. It is interesting to study the effects of increasing the demand, because we argue that the higher service level provided by this system will attract a substantially larger amount of passengers. We utilize solutions of the FSNDP with the demand as described in Subsection 7.2.4. The adjustments of the demand considered in the following

Table 12.2: Overview of cases for the C-DAR-FS test instances. Test instances are based on combinations of these cases, and the base case test instance is given below.

	Total fleet size	**Ferry allocation**	**Demand**	**Threshold**	**Minimum frequency**	**FSNDP ports**
Cases	V	FS-DAR	Low Regular High	Δ^{Thres}	Disregarded Imposed	Reduced Full
Base	*10/20*	-	*Regular*	*0*	*Disregarded*	*Full*

analyses should not affect the solutions of the FSNDP to a great extent, because it is the relative size of the demand between the OD-pairs that influences the solution, and this is not changed. Thirdly, we analyze the effects of changing the threshold value, Δ^{Thres}, which affects the allocation of a request between the fixed schedule and the DAR-service. We test for values of Δ^{Thres} between 0 and 20.

Furthermore, we consider two effects relating to cases from the FSNDP, which are *disregarded* and *imposed* minimum required frequencies, and the *reduced* and *full* ports, as defined in Section 7.1. These cases only affect the FSNDP solution, but we are interested in the effects on the C-DAR-FS when the fixed schedule interacts with the DAR-service. Recall that the *imposed* minimum required frequencies represent a service with significantly improved customer service (higher departure frequencies) than the current offering. All OD-pairs are ensured to have at least one departure per hour, and thus these requirements may be rather strict.

The test instances are generated by combining the various cases, and an overview of the considered cases is given in Table 12.2. Note that we consider two base case test instances, one with fleet size 10 and the other with fleet size 20. Both base case test instances have *regular* demand, a threshold value of 0, *disregarded* minimum frequencies and the *full* FSNDP port case.

12.2 Computational Results

This section presents the computational results from the simulation of various test instances. Firstly, we state some technical solution attributes and general observations of the C-DAR-FS. Secondly, we introduce the two main solution attributes of interest for managerial analyses, along with a more detailed analysis of these for a given fleet size. Then, to provide a thorough evaluation of the C-DAR-FS, we continue with several analyses of how different parameters affect the solutions of the simulation system for the C-DAR-FS. The following test instances in this section are the base case instances with varying ferry allocation, unless stated otherwise.

The fleet size has insignificant impact on the simulation time required to simulate the system for 400 hours of ferry operations. The average simulation time required across test instances with different ferry allocations is approximately two hours for the base case, regardless of fleet size 10 or 20. However, the number of requests has a significant impact. In the *low* and *high* demand case, the average simulation time required across all ferry allocations is five minutes and nine hours, respectively.

Moreover, we observe that the average percent of time the ferries are empty varies between the two service types for the base case with fleet size 20. Each DAR-ferry is empty, i.e. serves no passengers, less than 1% of an hour, while the FS-ferries are empty approximately 12% of the simulation horizon. When a DAR-ferry is empty, it waits in the port for another request, and is thus considered idle. An FS-ferry on the other hand operates its schedule regardless of the number of passengers on board.

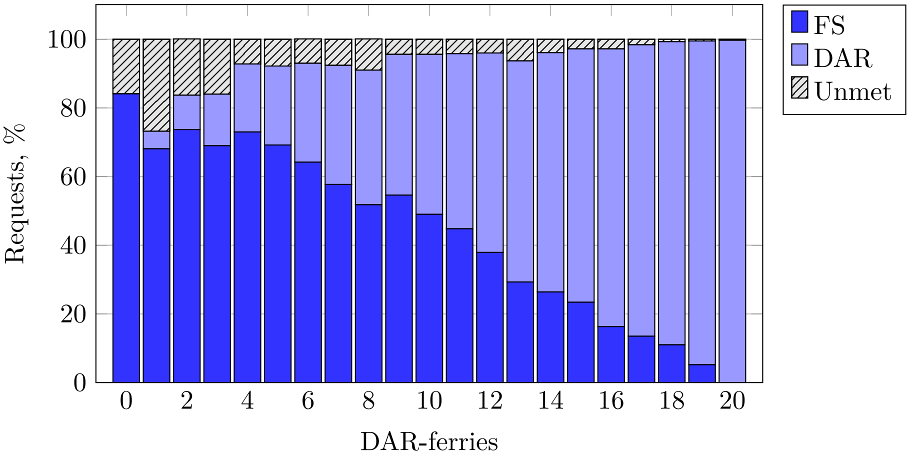
12.2.1 Analysis of Met Request Percentage and Service Time

Since the C-DAR-FS use case concerns public transportation, we aim to maximize the percentage of met requests while minimizing the average *excess service time*. The excess service time for a passenger is defined as the sum of the waiting time and the excess transit time of the passenger, because the remaining time, i.e. the direct transit time, is the minimum time required to serve the request. The average excess service time is calculated as a weighted sum of all passengers across all met requests.

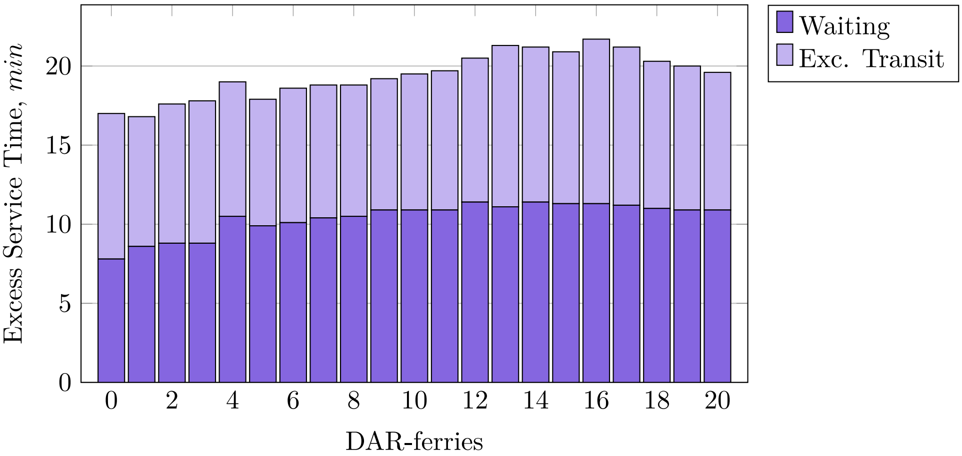
The first analysis to be presented is based on the base case test instance with fleet size 20, and we observe changes in the solution attributes for varying distributions of the ferries between the DAR-service and fixed schedule. The solution attribute concerning met requests is visualized in Figure 12.1a, where the distribution of requests between the DAR-ferries, FS-ferries, and what is considered unmet is given. For the same test instance, the second solution attribute concerning the average excess service time is plotted in Figure 12.1b, where the split between waiting time and excess transit time is also presented. We observe that the percentage of met requests increases with more allocated DAR-ferries, whilst the excess service time is at its minimum for more allocated FS-ferries. Thus, there appears to exist a trade-off between the two objectives with respect to the ferry allocation between the two services. However, we emphasize that these findings are specific to a fleet size of 20 ferries, and analyses of several fleet sizes must be conducted to find a general trend for optimal ferry allocations. This is performed in Subsection 12.2.2.

Moreover, Figure 12.1a shows that the percentage of met requests by the DAR-ferries increases seemingly linearly with the number of allocated DAR-ferries. A more detailed review yields that the distribution of met requests between the two service types appears to correspond with the allocation ratio. As two examples for fleet size 20, with three DAR-ferries, they service 18% of the met requests, and with 17 DAR-ferries, they service 86% of the met requests.

Figure 12.1b displays that the average excess service time increases with the number of DAR-ferries, before dropping slightly from 16 DAR-ferries and up. This



(a) Allocation of requests for varying distributions of the ferries between the DAR- and FS-service with fleet size 20 split between the two service types and unmet.



(b) Average excess service time for varying distributions of the ferries between the DAR- and FS-service with fleet size 20 with distribution of waiting time and excess transit time.

Figure 12.1: Met request percentage and average excess service time for different allocations of the ferries on the fixed schedule and the DAR-service with fleet size 20 in the base case. Note that an increase in the number of DAR-ferries equals an equivalent decrease in the number of FS-ferries.

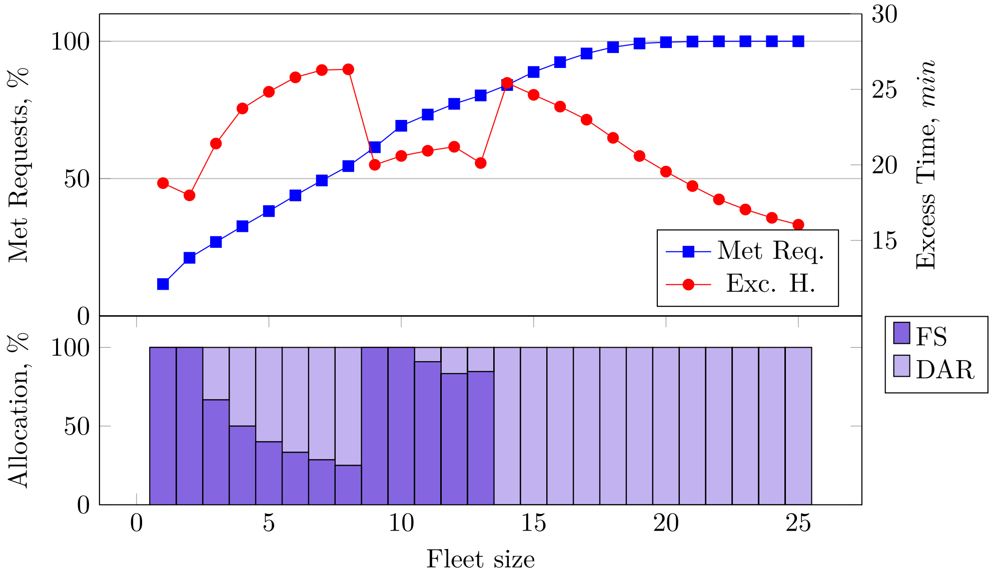
corresponds to the point where the met requests percentage is close to 100 percent. The excess service time per passenger is split almost equally between waiting time and excess transit time, thus on average approximately ten minutes are spent waiting in the port and on a ferry detour per passenger with a fleet size of 20.

12.2.2 Fleet Size Analysis

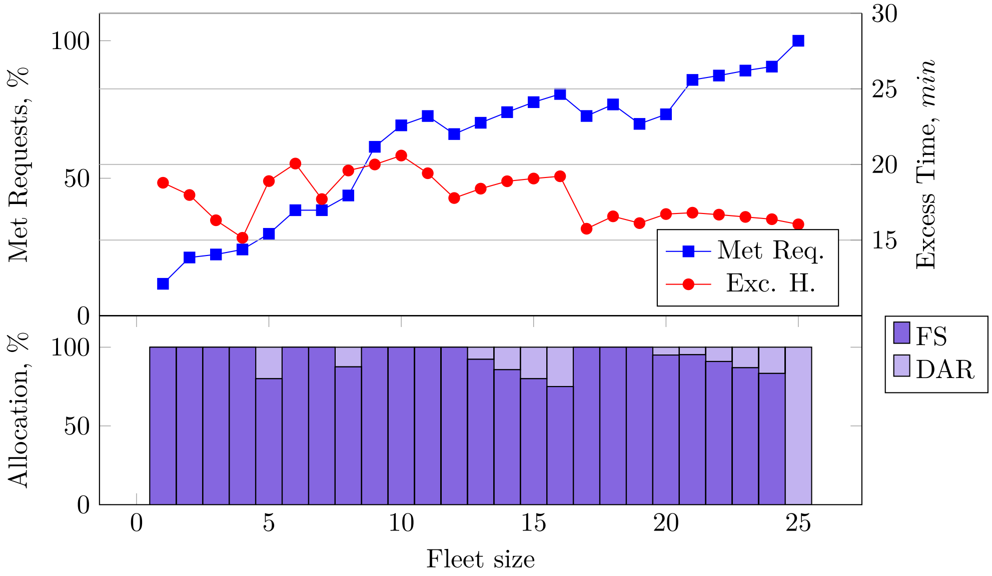
To investigate how many ferries is required to provide a high level of customer service, we perform an analysis of fleet size. For each fleet size, one may allocate either all ferries to the FS-service or the DAR-service, or a combination, which yields many allocation configurations. Thus, this analysis also provides a more detailed picture on how different ferry allocations affect the solution attributes of the C-DAR-FS. We could have conducted a bi-objective analysis if we had identified an appropriate weighting between the objectives of maximizing met requests and minimizing excess service time. However, the bi-objective analysis would have had to be performed for each fleet size, so we instead choose to present the allocations which incur the two extremes. Then, we can evaluate the impact of changing the fleet size in compact overviews, while also gaining some insights into the trade-off between the two objectives.

We test fleet sizes from zero to 30 ferries for the *regular* demand case. We analyse how the different fleet sizes perform, and what is the optimal ferry allocation with respect to maximizing the met request percentage or minimizing the average excess service time, for each given fleet size. The analysis was conducted with parameters from the base case test instances, except for the fleet size. Figure 12.2 displays two graphs. Figure 12.2a displays the met request percentage and the average excess service time for the allocation which maximizes the met request percentage. The optimal allocation ratio between the two service types is visualized by the purple bars below the graph. Figure 12.2b displays the same numbers but for the ferry allocation which minimizes average excess service time. Recall that all requests are considered met as long as they can be served within the given service quality requirement and ferry capacity. When testing, we found that from fleet size 25 and up, the optimal solution consists of only DAR-ferries with respect to both solution attributes, and the solutions have 100% met requests and low excess service times. Hence, this is the tipping point for where the flexibility of the DAR-ferries outweighs the predictability of the FS-ferries.

When choosing the allocation which maximizes the met request percentage, the percentage appears to increase linearly before flattening out and approaching 100% around fleet size 20. Moreover, we identify three areas of interest in the graph. First, considering a fleet size of one to eight, we observe that the FS-ferries are initially preferred, but then an increase in fleet size tends to increase the number of allocated DAR-ferries. Meanwhile the excess service time increases, so more passengers are served at the cost of increased waiting and excess transit times. Secondly, considering a fleet size of nine to 13, we see a sudden change to a fleet mostly consisting of FS-ferries. It may seem like the FSNDP has enough ferries to find a better service network configuration with nine ferries and up. Interestingly



(a) Allocation which maximizes the met requests.



(b) Allocation which minimizes the excess service time.

Figure 12.2: Percentage of met requests and corresponding excess service time for increasing total fleet size when selecting the ferry allocation which maximizes met requests or minimizes the average excess service time per passenger for each given fleet size. The number of ferries allocated to the DAR- and FS-service for the optimal instance is displayed for each fleet size by the relative fill of the bar. Test instances are computed with *regular* demand.

enough, the excess service time drops around five minutes per person in this fleet size area. Thirdly, we consider a fleet size of 14 and up. Here the total fleet is allocated to the DAR-service, albeit at a slightly higher excess service time. However, the excess service time decreases steadily with larger total fleet size, implying that the simulation model manages to utilize the flexibility of the DAR-service by first meeting more requests, and then aiming to reduce the passengers' excess service time. At fleet size 21, all requests are met.

When considering Figure 12.2b, which displays the allocation that minimizes the average excess service time, the optimal ferry allocation mainly consists of FS-ferries for all fleet sizes up to 24. It seems that when focusing on minimizing excess service time, the predictability of the FS-ferries yields better solutions. The excess service time remains fairly stable for all fleet sizes, ranging between 15 and 20 minutes. Also here, the met request percentage increases with the fleet size, although not linearly. This may be due to the varying solutions of the FSNDP with respect to fleet size.

In general, we observe that the excess service time increases up to 8.5 minutes per passenger when focusing on maximizing met requests. However, the average difference is 3.5 minutes, indicating that choosing allocations based on maximizing met request percentage may yield good solutions also with respect to low excess service times. However, when the operator is aware of the available total fleet size, he/she could evaluate each allocation combination for the two services and select the trade-off between the two solution attributes of his/her choosing.

12.2.3 Demand Analysis

In the following we study how the C-DAR-FS performs with different demand cases. We test selected instances for a total fleet size of 10 and 20 ferries, and for the three demand cases. The average number of requests per hour in the *regular* demand case is 538, while in the *low* case it is 170 and in the *high* case it is 1,654. With an average of 3.5 passengers per request, these demand cases represent 594, 1,884 and 5,790 passengers per hour. First, we present the two main solution attributes of interest; met requests and excess service time. Afterward, we continue by presenting an overview of the average number of passengers on board the two service types.

The two main solution attributes, i.e. the met request percentage and excess service time, are presented in Table 12.3 for selected test instances. An overview of all test instances is given in Appendix F. The first column (*Instance*) displays the instance name by the allocation of the fleet, where the first number represents the number of FS-ferries, and the second is the number of DAR-ferries. The following three groups of columns display solution attributes for the *low*, *regular* and *high* demand cases. Within each group, the first column (*Req*) displays the percentage of met requests within the given service requirements. The second column ($ExcT$) displays the average excess service time in minutes for the given test instance. Recall that the demand is tripled between each of the three demand cases.

As expected, a larger fleet size provides better service quality with respect to both

Table 12.3: Percentage of met requests (*Req, %*) and the corresponding average excess service time in minutes (*ExcT, min*) for selected test instances with the three demand cases and two fleet sizes, including varying allocation of the fleet between the fixed schedule and DAR-service.

Instance	**Low**		**Regular**		**High**	
(FS-DAR)	Req, %	ExcT, *min*	Req, %	ExcT, *min*	Req, %	ExcT, *min*
V = 10						
10-0	71.9	20.0	69.2	20.6	34.6	28.6
7-3	65.2	22.2	54.2	21.9	34.9	21.0
5-5	74.8	24.2	62.8	24.6	33.0	28.0
3-7	78.3	25.8	60.6	25.8	31.9	28.3
0-10	85.8	26.4	63.6	28.1	23.8	35.6
V = 20						
20-0	84.5	17.0	84.1	17.0	55.8	29.2
17-3	86.9	18.0	84.0	17.8	57.2	27.3
14-6	94.9	18.3	92.9	18.6	57.0	29.6
10-10	98.6	18.2	95.6	19.4	57.7	29.4
6-14	99.9	17.8	96.1	21.2	56.1	28.1
3-17	100	16.2	98.4	21.2	54.5	29.9
0-20	100	14.9	99.7	19.6	49.3	32.9

solution attributes. Moreover, the met request percentage decreases with increased demand, because the ferries have a limited capacity of 100 passengers. Note that with fleet size 20, the effects of increasing the number of allocated DAR-ferries has a positive effect on the percentage of met requests for the *low* and *regular* demand case, while in the *high* case it is beneficial to allocate more FS-ferries. However, with a fleet size of 10, the percentage of met requests changes more ambiguously. In the *low* and *regular* demand case, instance 7-3 sees a drop in met request percentage, whereas 10-0 and 5-5 are better. Thus, it seems that the FSNDP has found a good service network with ten FS-ferries which cannot be serviced by only seven.

For the instances with *low* demand, the met request percentage reach 100% between 14 and 17 ferries allocated to the DAR-service. Notice also, that with fleet size of 20, the excess service time is at its minimum in the instance with all ferries allocated to the DAR-service. This implies that with a sufficient size of the fleet, a DAR-service alone might be the best way to serve the passengers in time periods with low demand.

Moving from *low* to *regular* demand, the percentage of met requests drops slightly, while the excess service time is almost unaffected (except for 6-14, 3-17 and 0-20). This implies that the capacity of the ferries is most often non-restrictive in these

Table 12.4: Average number of passengers on board per hour on the two service types for selected test instances with the three demand cases and two fleet sizes, including varying allocation of the fleet between the fixed schedule and DAR service.

Instance	**Low**		**Regular**		**High**	
(FS-DAR)	FS *pas.*	DAR *pas.*	FS *pas.*	DAR *pas.*	FS *pas.*	DAR *pas.*
V = 10						
9-1	16	31	50	70	72	79
5-5	12	31	40	72	67	78
1-9	8	29	31	69	62	77
V = 20						
19-1	8	26	24	60	63	81
15-5	10	17	33	47	71	79
10-10	9	16	34	45	73	78
5-15	6	15	25	48	65	78
1-19	4	12	16	43	61	77

two demand cases, and thus the ferry service can manage demand in this range without affecting the service quality significantly. However, moving to the *high* demand, there is a large drop in the percentage of met requests and the excess service time surges. Capacity is now reached, and the network attempts to serve as many requests as possible, despite longer waiting times and detours. The DAR-ferries do not seem to handle the increased demand efficiently, and thus the need for a predictable fixed schedule arises. Here, increasing the number of FS-ferries appears beneficial considering both solution solution attributes.

Lastly, when looking at the average number of passengers on board each service type, we observe a difference between the fixed schedule and the DAR-service. Table 12.4 displays the average number of passengers on board a single ferry of each service type per hour for selected test instances and the three demand cases. The first column (*Instance*) displays the instance name as explained above. The DAR-ferries appear to have a larger number of passengers on board per hour than the FS-service, regardless of the allocation ratio. This may be due to the fact that the DAR-service is routed based on demand. The capacity of 100 passengers appears to be binding somewhere between the *regular* and *high* demand. By studying these two demand cases for a fleet size of 10, we observe that the average number of passengers on board the DAR-ferries only slightly increase, while this number almost doubles for the FS-ferries. Thus, it seems the DAR-ferries have reached their capacity limit, and the FS-ferries must serve more passengers.

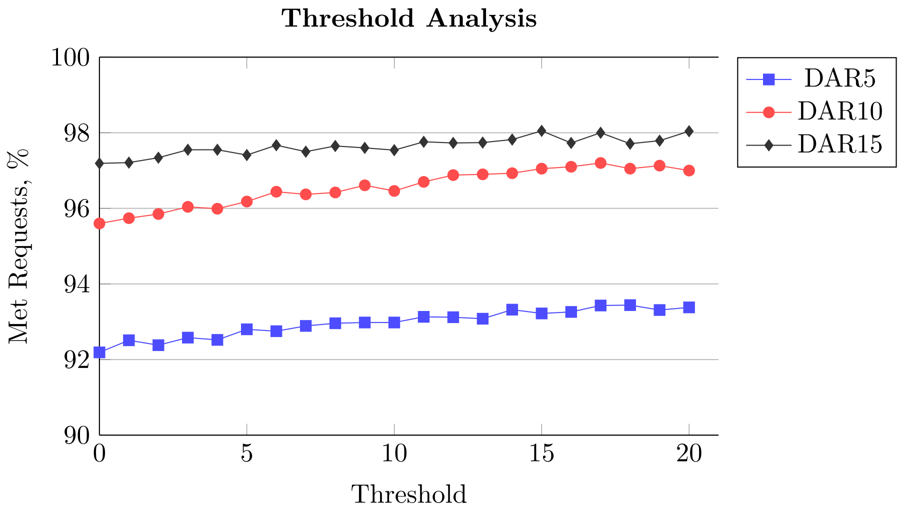


Figure 12.3: Percentage of met requests for increasing values of the threshold parameter, Δ^{Thres}, with a fleet size of 20 in the *regular* demand case. Fleet allocations with 5, 10 and 15 DAR-ferries are plotted, i.e. instances 15-5, 10-10 and 5-15.

12.2.4 Impact of Threshold

Recall from Chapter 10 that we introduced a threshold value, Δ^{Thres}, which is used when comparing the best assignment on DAR with the best assignment on the fixed schedule. If $t^{Service}_{i,DAR} \cdot n_i + \Delta t_{i,DAR} < t^{Service}_{i,FS} \cdot n_i + \Delta t_{i,FS}$, request i is assigned to the DAR-service. $\Delta t_{i,FS}$, is given by $\Delta t_{i,FS} = -\Delta^{Thres} \cdot n_i$, which implies that the DAR-service must deliver each passenger of the request in consideration at least Δ^{Thres} minutes faster than the fixed schedule service. Until now, the test instances have been computed with $\Delta^{Thres} = 0$, which implies that there has been no incentive to prefer an allocation to the FS-service rather than the DAR-service. In this section, we perform an analysis on how different values of Δ^{Thres} affects the performance of the C-DAR-FS. We tested the effect of threshold on instances with a fleet size of 20, where 5, 10, and 15 ferries are allocated to the DAR-service. Δ^{Thres} was set to values between zero and 20.

Figure 12.3 displays how increasing threshold affects the met request percentage. The excess service time was almost unaffected, remaining stable around 18, 19.5 and 21 minutes for five, ten and 15 DAR-ferries, respectively. We see a slight increase in the met request percentage, approaching two percent points for the case of five DAR-ferries. An increase of two percent points corresponds to approximately 40 passengers per hour. Thus, it seems like a threshold somewhat can increase the performance of the simple insertion heuristic, in particular if more FS-ferries are allocated, because with fewer DAR-ferries the significance of the flexibility offered by the DAR-service increases. Note, however, that the allocation of ferries to the

Table 12.5: Percentage of met requests and the corresponding average excess service time in minutes for test instances with the FSNDP solved for the *disregarded* and *imposed* minimum required frequency case.

Instance	**Met Requests,** %			**Avg. Excess Time,** *min*		
(FS-DAR)	Max case	*Dis*	*Imp*	Min case	*Dis*	*Imp*
20-0	Imp	84.1	96.8	Dis	17.0	19.8
19-1	Imp	73.3	97.5	Dis	16.7	18.9
18-2	Imp	83.6	98.4	Dis	17.6	18.4
17-3	Imp	84.0	97.0	Dis	17.8	18.9
16-4	Imp	92.8	97.4	Imp	19.1	18.9

fixed schedule or the DAR-service affects the performance measures to a much larger degree than the threshold value. This implies that the proposed objective, which considers both the passengers of the request in consideration and the extra service time for the already assigned requests, appears to reduce the need for a threshold value.

12.2.5 Imposed Minimum Required Frequencies

In the following we analyze how the minimum required frequency constraints affect the solutions of the C-DAR-FS. We tested the base case instance with a fleet size of 20 for the two minimum frequency cases. Table 12.5 displays the met request percentage and the average excess service time for the test instances with minimum required frequency cases *disregarded* (base case, column *Dis*) and *imposed* (column *Imp*). It also displays the best case considering maximizing the met request percentage (*max case*) and minimizing the average excess service time per passenger (*min case*). The table only includes allocations with at least 16 FS-ferries, because the FSNDP is infeasible for less than 16 ferries with *imposed* minimum required frequencies. Note that without minimum required frequencies imposed, it is preferable to allocate more than four ferries to the DAR-service. However, we perform this analysis to see if it is beneficial to allocate more ferries to the fixed schedule when minimum required frequencies are imposed.

Solving the FSNDP with *imposed* minimum frequencies appears to yield a large increase in met requests for the C-DAR-FS with only a minor increase in excess service time per passenger. Recall from Figure 12.1 that the base case test instance with fleet size 20 has the highest percent of met requests for allocations of 15 DAR-ferries and up. The allocation with 5 FS-ferries and 15 DAR-ferries has 97.2% met requests with 21 minutes excess service time with *disregarded* minimum required frequencies. Now considering the solutions with *imposed* frequencies, we observe that the solution quality with 16 or more FS-ferries is comparable to that of 15 or more DAR-ferries with respect to both solution attributes. This is interesting, because it opens for the possibility of allocating more FS-ferries to provide customers

Table 12.6: Percentage of met requests (*Req, %*) and the corresponding average excess service time (*ExcT, min*) in minutes for selected test instances with the FSNDP solved for the *full* and *reduced* port case with *regular* demand. For the *reduced* port case, results are displayed for both the *disregarded* and *imposed* minimum required frequency cases.

Instance	**Reduced, disreg.**		**Reduced, imposed**		**Full, disreg.**	
(FS-DAR)	Req, %	ExcT, *min*	Req, %	ExcT, *min*	Req, %	ExcT, *min*
V = 10						
10-0	35.0	16.4	38.4	17.7	69.2	20.6
7-3	46.9	22.4	54.4	22.1	54.2	21.9
5-5	54.8	24.9	-	-	62.8	24.6
3-7	56.0	26.8	-	-	60.6	25.8
1-9	61.4	28.0	-	-	64.8	27.2
V = 20						
20-0	38.4	12.7	38.4	12.7	84.1	17.0
16-4	60.4	19.7	60.4	19.7	92.8	19.1
13-7	74.3	21.0	74.3	21.0	92.4	18.8
10-10	83.9	21.1	85.5	21.1	95.6	19.4
7-13	90.3	21.1	93.3	20.3	93.7	21.2
4-16	95.8	20.8	-	-	97.2	21.7
1-19	99.3	20.2	-	-	99.5	20.0

with increased predictability, without affecting the service quality significantly.

Due to the increased solution quality, this analysis motivates for further studies of the minimum required frequencies, where the constraint parameters are tuned, such that feasible solutions can be identified for FSNDP instances with a smaller fleet. The *imposed* case considered here is rather strict by imposing hourly departures between all OD-pairs in the network. Thus, it may be interesting to study cases where departures are only ensured between selected, important OD-pairs.

12.2.6 Reduced Port Case for the Fixed Schedule

Recall that all test instances of the C-DAR-FS are solved with the *full* port case, comprising all the ten ports that are operative in Kiel today. However, in Part I, the FSNDP was solved both for a *reduced* port case and the *full* port case. In this section we analyze the performance of the C-DAR-FS when using the FSNDP solved for the *reduced* port case as base for the fixed schedule. This implies that the fixed scheduled services operate these large ports, while the DAR-ferries primarily serve the remaining smaller ports.

Table 12.6 displays the average met request percentage and the average excess service time in minutes for selected test instances with *regular* demand where the FSNDP is solved with the *reduced* port case, both with the minimum required frequencies *disregarded* (columns *Reduced, disreg.*) and *imposed* (columns *Reduced, imposed*). An overview of all test instances is given in Appendix G. We compare these results with our base case for the C-DAR-FS, i.e with the FSNDP solved with the *full* port case and the minimum required frequencies *disregarded* (columns *Full, disreg.*).

We observe that the FSNDP solved with the *full* port case, has a significantly higher met request percentage than the *reduced* port case in most instances, both with and without minimum required frequencies imposed. The only exception is the case with seven FS-ferries and three DAR-ferries, i.e. 7-3, where the met request percentage is marginally better in the case where the FSNDP is solved with the *reduced* port case and minimum required frequencies *imposed*.

As for average excess service time, it is more even between the two port cases. Also here, the solutions with the *full* port case are mostly better, but the differences are smaller. Moreover, there are a few more cases where the solutions with the *reduced* port case, either with the minimum required frequencies *imposed* or *disregarded*, have smaller average excess service time, but in these cases the differences are negligible. However, a significant difference is observed in the instances with 20 FS-ferries and zero DAR-ferries. Here it appears like the FSNDP-solution solved with the *reduced* port case has resulted in more efficient routes, as the average excess service time is quite a few minutes shorter. Note however that the met request percentage is very poor for the instances solved with the *reduced* port case.

We observed in Part I that the solution for instances solved with the *reduced* port case sometimes performed better regarding transit times. For some instances we can see tendencies to this here also, but the met request percentage is mostly very poor. Overall, the FSNDP solved with the *full* port case, clearly outperforms the FSNDP solved with the *reduced* port case, both with and without minimum required frequencies imposed, and thus we conclude that when solving the C-DAR-FS it seems favorable to set the fixed schedule based on a FSNDP instance solved for all ports.

12.2.7 Extended Port Case with the DAR-Service

Lastly, we consider the inclusion of the three seasonal ports displayed in Figure 2.1, which may be served by the DAR-service. The FSNDP has only been solved up to ten ports, so in this subsection we evaluate the C-DAR-FS for an *extended* port case with 13 ports, while the fixed schedule is solved for the *full* port case with ten ports.

To present the attributes of the seasonal ports, we extend Table 7.1 with three additional rows in Table 12.7. All the seasonal ports are located in the north of the fjord, and the ports of Schilksee and Strande lie close together. Note that when adding more ports, we also add new OD-pairs, which generates more requests according to their demand size. Thus, the total demand in the system will increase.

Table 12.7: Description of seasonal ports in the *extended* port case for test instances, including selected attributes.

No.	Port name	Size	Well con.	Adj.	N/S
10	Falkenstein	S	-	-	7
11	Schilksee	M	12	12	8
12	Strande	S	11	11	9

We tested the C-DAR-FS with the *extended* port case for test instances with *regular* demand. Moreover, we tested for fleet sizes of 10 and 20 ferries with all allocation possibilities. The fixed schedule is based on the FSNDP solutions for *disregarded* minimum required frequencies, and as previously mentioned, the *full* port case. With the additional seasonal ports, the average number of requests per hour is 788, implying an average number of 2,758 passengers per hour. This indicates that by opening the three additional ports, the system sees an increase of 874 additional passengers per hour. In Table 12.8 we display the met request percentage (*Req*) and the average excess service time (*ExcT*) in minutes for a selection of the ferry allocations for the two tested fleet sizes.

In general, the met request percentage appears rather low, and as an example it is reduced by 19.8% percentage points for instance 10-10 compared to the *regular* demand and *full* port case displayed in Table 12.3. Moreover, we observe that the excess service time increases with more DAR-ferries. This trend has also been observed previously with increase in demand. However, here it could be further enhanced by the higher waiting times associated with the longer distances the DAR-ferries are required to travel to serve the new northern ports. Note that with all ferries allocated to the fixed schedule, the additional ports can not be served. However, with only 10 ferries, all ferries should still be allocated to the fixed schedule to serve the most demand in the shortest time. Then, the FS-ferries serve the southern ports more efficiently than a combined allocation can serve all ports. For the case with a fleet of 20 ferries, we see that the met request percentage is maximized when 10 ferries are allocated to the fixed schedule and 10 ferries are allocated to the DAR-service, and we notice that this is a sweet spot where also the excess service time appears relatively low.

The observations indicate that a fleet size of 10 is too small to serve this case, and also with a fleet size of 20 ferries, there is a substantial percentage of unmet requests within the maximum waiting and service time. This implies that in periods where there is demand to and from the seasonal ports, the operator may need to deploy a larger fleet. Moreover, we observe that the solution attributes vary significantly with respect to the allocation of ferries. Thus, the allocation of the ferries must be adjusted to the specific fleet size available.

By allowing some ports to be solely served by the DAR-service, the C-DAR-FS may provide insights for ferry services with larger port cases than the FSNDP itself can solve, within reasonable computational time. Thus, as shown here, an assessment

Table 12.8: Solution attributes for selected test instances of the C-DAR-FS evaluated with the *extended* port case. The table displays the percentage of met requests (*Req, %*) and the corresponding average excess service time (*ExcT, min*) in minutes for test instances with *regular* demand and the FSNDP solved for the *full* port case and minimum required frequencies *disregarded.*

Instance	**Extended**	
(FS-DAR)	Req, %	ExcT, *min*
V = 10		
10-0	47.4	20.6
7-3	35.9	23.7
5-5	41.2	27.8
3-7	38.0	29.1
0-10	36.7	34.5
V = 20		
20-0	57.6	17.0
16-4	70.6	23.1
13-7	70.3	23.6
10-10	75.8	25.7
7-13	65.9	27.5
4-16	66.0	28.8
0-20	69.6	30.1

of adding new ports, e.g. seasonal, can easily be performed with the simulation system. Moreover as a final remark, other use cases with more ports than the Kiel fjord may benefit from the C-DAR-FS by combining two (or more) fixed schedule systems with a DAR-service. If the ports may somewhat be divided into two or more ”groups” to be solved with their respective FSNDP, fixed schedule departures may exist across the entire network, and when combined in the C-DAR-FS with DAR-ferries, connections across the groups may be provided by the DAR-service.

12.3 Managerial Insights

After having evaluated the effect of changing various parameter values, we attempt to provide some general observations and managerial insights related to the C-DAR-FS. We have considered the number of met requests and the excess service time per passenger as the two key solution attributes to measure service quality. Firstly, as expected, we observed that different allocations for a given fleet size yield different solution attributes. We have discovered that there may exist trade-offs between increasing the number of met requests and decreasing the excess service time. Thus, the optimal allocation depends on the preferred weighting between the two solution attributes.

Secondly, we have seen that the preferable allocation between the fixed schedule and the DAR-service, with respect to the two solution attributes, depends to a large extent on the available fleet size. Overall, the predictability of a fleet mainly consisting of FS-ferries, supplemented by a few DAR-ferries, provides the best customer service when the fleet size is below 14. However, from a fleet size of 14 and up to 24, a full DAR-service serves the most requests, albeit with higher excess service times than a fleet of mainly FS-ferries. Considering a large fleet of over 25 ferries, the responsiveness of the DAR-service fully outweighs the predictability of the fixed service, and is thus preferable with respect to both met requests and excess service time.

Thirdly, the demand affects the optimal allocation significantly. In periods of low demand, we recommend allocating more ferries to the DAR-service due to their flexible and responsive behavior, whereas in periods with increased demand, the predictability of the FS-ferries becomes preferable. For period with moderate demand, we found that a combination of a fixed schedule and DAR-service may provide the highest service quality.

Lastly, we have seen that the best performance is yielded when the fixed schedule is based on an FSNDP-solution comprising all considered ports by the C-DAR-FS. However, we also evaluated the C-DAR-FS for an extended port case including the seasonal ports, where the added ports are served solely by the DAR-service. We see that the simulation system of the C-DAR-FS supports an increase in the number of included ports while remaining solvable within reasonable time. This enables an easy assessment of establishing new port locations served by the DAR-service.

Chapter 13

Concluding Remarks

In this thesis, we have presented and discussed methods to provide decision support to the implementation of a ferry service for public passenger transportation in the Kiel fjord using autonomous passenger ferries. Firstly, we formulated a mathematical model denoted the Ferry Service Network Design Problem (FSNDP), which may be used as a decision support tool to create fixed schedule departures. Secondly, we presented a combined transportation system, where a fixed schedule based on the solution of the FSNDP is supplemented by a *dial-a-ride* service which enables ferries to be called upon and rerouted, much like a rideshare taxi service. We denoted this system the Combined Dial-a-Ride and Fixed Schedule for a Ferry Service (C-DAR-FS).

The solution network provided by the FSNDP consists of a set of routes with given departure frequencies. To supplement current service network design literature, we introduced *minimum required frequencies* per OD-pair, which enable control over the available connections offered by the network. Moreover, we argued that passengers in a public transportation network are willing to accept a certain level of excess transit time for the benefit of increased departure frequencies, which lead us to construct non-linear user utility functions. In addition to the model formulation, we proposed a route generation algorithm for chain structures, which generates candidate route and frequency combinations a priori. To limit the number of combinations, we extracted the procedure of identifying where the waiting time between departures should occur into a preprocessing step.

We introduced the C-DAR-FS to evaluate if a fixed schedule ferry service can benefit from being supplemented by a more flexible dial-a-ride service. For a given ferry fleet, the optimal allocation of ferries between the fixed schedule provided by the FSNDP and the DAR-service was assessed by constructing a simulation system. This simulation system contained a request assignment procedure in which requests are assigned to one of the services according to given service level requirements. Moreover, we developed an insertion heuristic to identify the best assignment on the DAR-service, which included the option to redirect a ferry underway.

The results of the analyses conducted indicate that the optimal fleet allocation to a large degree depends on the demand level. Peak hours with high demand may benefit from the predictability of the fixed schedule, whereas off-peak periods with reduced demand is suitable for more DAR-ferries due to their flexible and responsive behavior. However, the optimal fleet allocation also varies significantly with the number of ferries in the fleet. With a smaller fleet, there is a tendency to prefer allocation to the fixed schedule, whereas with a sufficiently large fleet, more demand can be served by allocating all ferries to the DAR-service. Since each allocation yields its own FSNDP-solution, the fixed schedule network changes its configuration. Therefore, there are discontinuities in the findings. When the fleet size to be implemented is known, an evaluation of the allocations should be performed to identify the preferred trade-off between the number of met requests and the corresponding service time.

Interestingly, when assessing the service quality using the simulation system, we observed that the ferry system can benefit from imposing minimum required frequencies per OD-pair when generating a fixed schedule with the FSNDP. For a fleet of 20 ferries and moderate demand, the system serves the most demand by allocating all ferries to the DAR-service. However, by imposing minimum frequency requirements per OD-pair, allocating more ferries to the fixed schedule could compete with a fleet of predominantly dial-a-ride ferries, when considering the level of customer service provided.

In addition to the aspect of servicing passengers within reasonable time, the operator should consider what kind of ferry service the passengers value. On the one hand, a service with many fixed schedule departures provides a predictable system, where the passengers can plan their journey after a schedule and choose their own waiting time. On the other hand, in a service with most ferries allocated to the DAR-service, the predictability is replaced by responsiveness, albeit with an arbitrary waiting time in the port of up to thirty minutes.

By utilizing the FSNDP and the C-DAR-FS as decision support tools, a complete ferry service design without the need for transfer can be obtained. The proposed models are also applicable for other use cases by identification of corresponding parameter values. For the specific case of the Kiel fjord we would recommend a fleet size of 15 to 20 ferries, where the ferry allocation varies during the day or year according to the demand. With more precise demand predictions and an investment in a fleet of 15 to 20 autonomous ferries, the level of customer service provided by the public ferry service offering in Kiel can be substantially improved, thereby also improving the total public transportation offering. This may enable more commuting by public transportation in the city of Kiel. Therefore, an upgraded ferry service may lead to ease of road congestion, unlocking the potential of the fjord, and connecting the east and west side with shorter transit times.

Chapter 14

Future Research

This chapter presents different suggestions for future research which may provide additional decision support for the planning of the public ferry service offering in Kiel. We base the propositions on results from Part I and Part II, knowledge acquired when studying the literature and an overall hindsight after the work with this thesis.

14.1 Alterations and Extensions to the FSNDP

We have seen that the FSNDP requires substantial computational time in order to generate routes for larger port cases than ten ports. To overcome this, it could be interesting to explore more efficient route generation algorithms, perhaps by using more heuristic methods, thereby generating a smaller set of routes. Another possibility is to develop a two-problem structure which combines generation of routes and optimization of the route network in an iterative process.

Moreover, we identify some extensions to the modeling of the FSNDP that could yield better ferry service networks. The first proposed extension to the model could be to introduce berthing times dependent on the expected demand to each port. This could generate more realistic transit times for the routes. Secondly, there are possibilities for fine tuning the utility functions in the objective. One idea is to adjust the transit time utility by the service level provided by alternative transportation, e.g. bus. Thus, well-connected OD-pairs could be associated with lower utilities to stimulate connections between OD-pairs with poor alternative transportation options. Lastly, we have considered rather strict minimum required frequencies, which have required at least 16 ferries to cover. Thus, we encourage further research into smart ways of formulating these frequencies to find the right balance between required fleet size and guaranteed service quality. A suggestion would be to link the minimum required frequencies more to the demand, and attempt to identify which OD-pairs should be regulated to have the largest impact on the solution.

14.2 Alterations to the Simulation System for the C-DAR-FS

For the simulation system we implemented, there are several possible improvements which may make the modeling more realistic. Firstly, by acquiring exact coordinate information for locations in the fjord, more correct pickup times can be calculated when redirecting the ferries. The coordinate information can relate to the port location and feasible travel paths between them, e.g. which parts of the fjord are deep enough for the ferries. Secondly, as for the FSNDP, berthing time could be modeled as a function of number of passengers em- and disembarking or other port specific attributes. Thirdly, to incorporate the ferry service with a complete public transportation offering, more realistic maximum waiting and service times could be obtained by investigating the public transportation offered by other transportation modes. Then, these travel times could be used as benchmarks.

Furthermore, there is a great potential related to identifying more realistic demand estimates. Since the allocation strategies are dependent on the size of the demand, the allocation may vary during the day. However, some transportation systems may not enable this, and thus, considering shifting demand during the simulation period may provide insights into a single optimal allocation for periods with varying demand. Moreover, it could be interesting to continue this research with an analysis on how an increasing service level affects the current demand for a ferry service in Kiel. With more detailed insights in the actual demand for the service, the C-DAR-FS may also be evaluated for varying ferry capacities, thereby possibly identifying an optimal ferry size.

Lastly, stochastic conditions could be implemented. For example a realistic modeling could be achieved by including some probability of the passengers canceling their request as a function of waiting time. Another possibility to incorporate stochastic conditions is to let sailing and berthing times be dependent on some probability distribution.

14.3 Other Modeling Approaches to the C-DAR-FS

The C-DAR-FS is assessed with a simulation system containing a rather simple insertion heuristic. If the simulation system was to be used for operating a ferry service, we would encourage future research regarding more sophisticated insertion methods. One option is to enable reshuffling of already assigned requests, when assigning new requests. Another option is to implement a partly static problem structure, where requests to the ferry service must be booked e.g. 30 minutes prior to pickup. This will aggregate requests to be assigned, which may provide better solutions, because the plans are based on some knowledge of the future. However, note that such a structure would imply a different type of service, where passengers no longer can just show up in their origin port and desire to travel as soon as possible.

When assigning requests to the DAR-service, the waiting time in the port for the passenger significantly impacts customer service. Thus, another possible alteration to the model is to implement ferry waiting strategies, such that the DAR-ferries travel to a more strategic waiting location when they are idle. The strategic location could be based on expected demand, and thereby the ferry may be able to pick up passengers sooner.

Moreover, when converting the solutions of the FSNDP to a timetable, more sophisticated methods can be used to identify good departures, e.g. distribute them from the ports more evenly over the hour. We would encourage to study literature on timetable optimization to achieve a sensible and efficient timetable to be used in C-DAR-FS framework.

Lastly, it could be interesting to model the system with an operator cost perspective, either in addition to the current objective or as a substitution. Currently, operator cost is considered through the given fleet size, but it may be extended to include ticket revenues from the passengers. The fare price could be differentiated between the two service types to encourage dial-a-ride services on poorly served OD-pairs, where the willingness to pay for a responsive service may be greater. Moreover, one could consider a dynamic price for the DAR-service according to the provided excess service time. Such a system would probably include prices related to specific excess service time ranges, because given the current system, requests may have their arrival time somewhat delayed if new requests are assigned underway.

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Appendices

Appendix A

Material Collection for the General Review of Network Design Problems

A.1 Passenger Transportation Network Design Literature

The search for relevant PTND literature was initialized by defining four groups of relevant keywords. All combinations of one word from each group are used as the search string, implying that the search criteria ”OR” is inserted between each word within a group, and that the search criteria ”AND” is used between the groups. The first group relates to the type of optimization problem, so it includes ”network design”, ”routing”, ”scheduling”, ”schedules” and ”route design”. To direct the search towards public transportation and our two topics, the second group forces the title to contain either ”public transport”, ”service network”, or ”bus”. The third group further defines the problem type by directing the search towards the transportation of passengers, and therefore it comprises the keywords ”passenger” and ”user”. Lastly, the fourth group aims to specify problem characteristics with the keywords ”frequency”, ”frequencies”, ”transit time”, ”service”, ”multi path”, and ”departure”.

The contents of the search string must either appear in the title, abstract or keywords of the articles. The initial search returned 1,764 papers. The search was narrowed to allow only English articles published in journals, which left 935 articles. Furthermore, irrelevant fields of study and associated irrelevant keywords (e.g. ”emission”, ”energy”, and ”sustainability”) were removed. This yielded 696 articles. Bus optimization in general often comprises subjects such as ”hub and spoke”, ”congestion”, ”traffic control”, ”bus bunching”, ”bus driver” and ”school bus". These keywords were disregarded in our search, because they are not discussed for the remainder of this thesis. Moreover, the search was further limited by removing keywords related to uncertainty, e.g "stochastic" and "sensitivity". Then, 393 articles were left in the search.

The search required further narrowing, so a manual screening of relevance in the abstracts was conducted. All articles discussing crew, school bus, congestion, and maintenance were removed, along with articles dealing with risk, stochasticity, robustness, and sensitivity. The most relevant papers were selected, and the final list of papers for a detailed review included seven papers. These are presented in the next subsection. The material collection process for PTND literature is illustrated in Figure A.1.

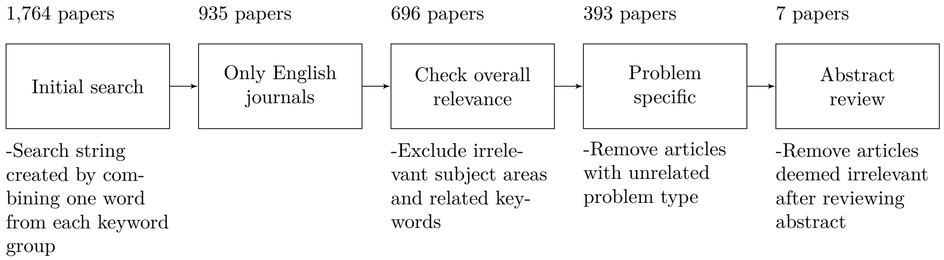

Figure A.1: Material collection process for PTND literature.

A.2 Liner Shipping Network Design Literature

As in the previous search, the set of relevant keywords used for searching relevant LSND literature is divided into four groups. The first group relates to operations research literature, so it includes "optimization", "mathematical model", "minimize" and "maximize". The second group specifies the search for LSND. Therefore, it only includes "liner shipping". The third group includes keywords related to the planning level of the problem, which are "network design", "routing" and "scheduling". Lastly, the fourth group aims to direct the search in the direction of the problem specific characteristics. Hence, this group has "varying frequency", "varying departure", "transit time", "service" and "multi path". Here, the expression "varying departure" is inserted, because some articles may discuss "departure" for a route rather than "frequency", even though both terms concern how many times the route is served.

The first search returned 999 papers, but removing articles that were not written in English or published in journal, yielded 756 papers. A further filtration was required. Therefore, irrelevant subject areas were excluded from the search, including social sciences, earth and planetary sciences, chemistry and psychology. In addition, keywords related to these areas were excluded, e.g. "game theory" from psychology and "emission control" from earth and planetary sciences. The result was 261 papers.

To further limit the search space, some challenges often related to liner shipping, but not the FSNDP, were excluded. The current problem does not consider uncertainty, speed optimization, empty container repositioning, hub and spoke networks, berth allocation and other modes of transport. Therefore, keywords related to these challenges were excluded from the search result, yielding only 125 papers.

The abstract of the 125 papers were reviewed to check for relevance to the FSNDP. Articles discussing container storage, qualitative surveys, empty containers, fuel consumption optimization and only vessel scheduling (not including network design) were filtered out. Also, duplicates were removed. This left seven papers to be reviewed in further detail, and these are presented in the next section. The material collection process for LSND literature is visualized in Figure A.2.

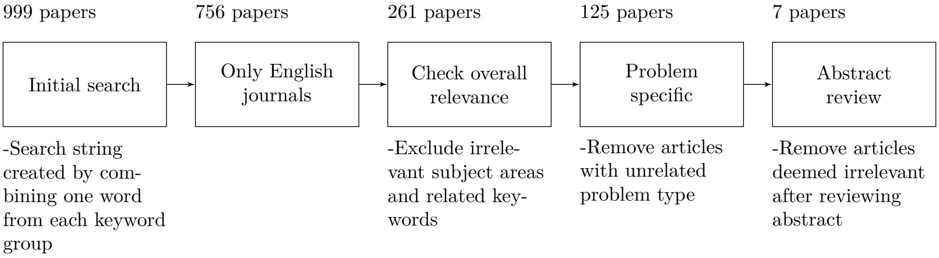

Figure A.2: Material collection process for LSND literature.

Appendix B

Route Heuristic

In the following we present a heuristic to reduce the number of routes from which to create candidate *rf*-combinations. The route heuristic compares the candidate routes which visit the exact same ports to analyze if some of them are ”better” than others. We define ”better” to be a route with less *excess passenger hours* than another. Excess passenger hours for a given route r, PH_r, is calculated by Equation B.1. A_{rimjn} is equal to one if the route serves the port pair within the maximum excess transit time, and T_{rimjn} is the transit time between the port pair on the given route.

$$PH_r = \sum_{i \in \mathcal{P}_r} \sum_{j \in \mathcal{P}_r} \sum_{m=1}^{M_i} \sum_{n=1}^{N_j} D_{ij} \cdot A_{rimjn} \cdot (T_{rimjn} - T_{ij}^{Direct}) \tag{B.1}$$

For all the routes containing the same ports, the route heuristic chooses the n routes with lowest excess passenger hours. All other routes visiting the exact same ports are disregarded. For example, consider a scenario were we have the routes $[A, B, C, D, A]$, $[A, C, D, B, A]$ and $[A, D, B, C, A]$. Assume the demand is large from A to D, and for this particular example, this is the dominating expected demand among the ports on these routes. Route $[A, D, B, C, A]$ transports these passengers most efficiently, because the passengers travel directly from A to D. Moreover, the route $[A, C, D, B, A]$ is better than route $[A, B, C, D, A]$. If we implement route heuristic 2 with $n = 2$, we select only the candidate routes $[A, C, D, B, A]$ and $[A, D, B, C, A]$.

Table B.1: Unique routes and *rf*-combinations for various values of n in the *reduced* and *full* port case.

n	**Reduced**		**Full**	
	Routes	*rf*	Routes	*rf*
1	178	812	14,797	66,506
2	307	1,393	28,770	129,250
3	362	1,644	40,475	181,844
4	417	1,895	51,996	233,760
5	429	1,950	60,828	273,424
6	441	2,010	69,330	311,496
7	453	2,063	77,284	347,332
8	465	2,121	85,136	382,703
9	466	2,128	91,167	409,870
10	467	2,135	97,157	436,838
inf	473	2,177	257,400	1,155,059

Algorithm 3 displays a pseudocode for the heuristic procedure.

Algorithm 3: Algorithm for describing the procedure of the route heuristic.

```
Input: All routes generated by route generation rules in Subsection 6.2.1
Sort the routes in sets comprising the same ports (and thus having the same length)
for all sets comprising the same ports do
    for all routes in a set do
        Calculate $PH_g$
    end
    Choose the $n$ routes with the lowest $PH_g$
end
```

We tested the effects of the route heuristic for the FSNDP. As Table B.1 displays, the number of routes and thus *rf*-combinations, increases significantly for the *full* port case compared to the *reduced.* When the route heuristic is not applied, it is denoted "$n = inf$".

The computational time required increases drastically for the *full* port case, so the route heuristic was applied for values of n ranging from one to ten. Each test was performed on five samples of demand, and the following results are reported as an average of the five samples. The average computational time and objective are presented in Figure B.1, where the computational time required is the sum of preprocessing and solving the optimization model itself.

The route heuristic appears to identify good solutions. The optimal solution is

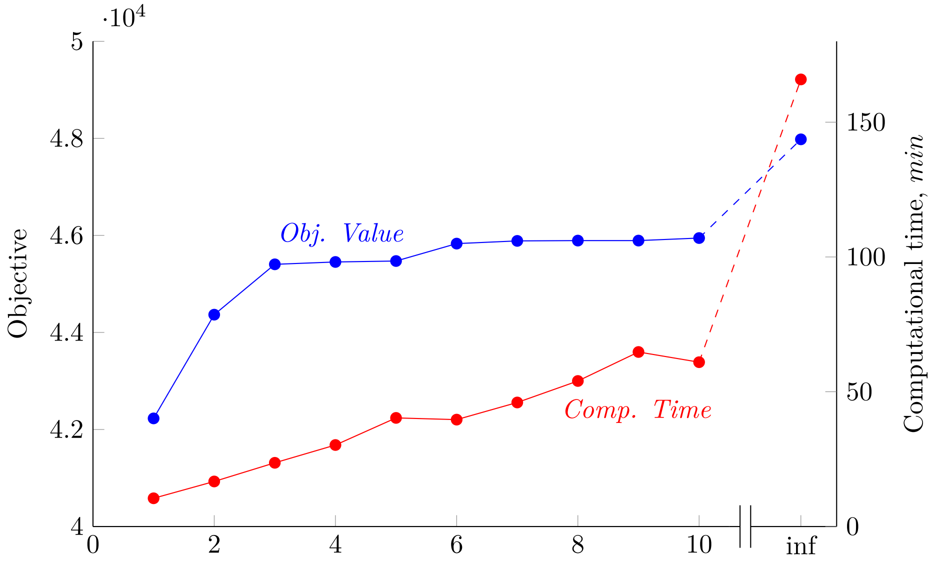

Figure B.1: Objective value and computational time for different values of n in the route heuristic for the *full* port case.

rather stable from $n = 3$, before increasing again slightly at $n = inf$. Even though the differences may appear great, the objective for $n = 2$ is only 7.5% less than the objective for $n = inf$, and at $n = 10$ it is 4.2% less. Furthermore, the computational time increases rather linearly, and exceeds one hour at $n = 9$. However, since the FSNDP is a strategic problem, the approximately three hours it takes to solve for $n = inf$ is acceptable. Therefore, the route heuristic is not applied in the test instances in this thesis, but may be applicable in larger test instances.

Appendix C

Distance Data

Table C.1: Direct distances (in *kilometers*) between all ports in the *full* port case (L_{ij}^{Direct}).

Port no.	0	1	2	3	4	5	6	7	8	9
0	0	3.61	6.63	9.65	9.9	11.32	10.24	9.05	7.61	3.37
1	3.61	0	3.22	6.15	6.41	7.86	6.79	5.66	4.27	1.83
2	6.63	3.22	0	3.3	3.55	4.92	3.84	2.72	1.55	4.26
3	9.65	6.15	3.3	0	0.266	3.65	2.57	1.72	2.41	7.27
4	9.9	6.41	3.55	0.266	0	3.9	2.82	1.97	2.66	7.52
5	11.32	7.86	4.92	3.65	3.9	0	1.12	2.35	3.9	8.84
6	10.24	6.79	3.84	2.57	2.82	1.12	0	1.27	2.84	7.79
7	9.05	5.66	2.72	1.72	1.97	2.35	1.27	0	1.74	6.67
8	7.61	4.27	1.55	2.41	2.66	3.9	2.84	1.74	0	5.14
9	3.37	1.83	4.26	7.27	7.52	8.84	7.79	6.67	5.14	0
10	1.51	2.96	5.87	8.97	9.22	10.54	9.48	8.42	6.97	2.66
11	3.88	6.51	9.34	12.54	12.79	14.41	13.33	12.19	10.8	6.36
12	4.49	7.15	10.05	13.18	13.43	15.05	13.95	12.81	11.42	6.98

Table C.2: Direct distances (in *kilometers*) from all ports to the seasonal ports (L_{ij}^{Direct}).

Port no.	10	11	12
0	1.51	3.88	4.49
1	2.96	6.51	7.15
2	5.87	9.34	10.05
3	8.97	12.54	13.18
4	9.22	12.79	13.43
5	10.54	14.41	15.05
6	9.48	13.33	13.95
7	8.42	12.19	12.81
8	6.97	10.8	11.42
9	2.66	6.36	6.98
10	0	4.02	4.64
11	4.02	0	1.03
12	4.64	1.03	0

Appendix D

Demand Data

Table D.1: *Average* demand based on the five demand samples used in the test instances for the FSNDP. The table displays the number of passengers wanting to travel from port i (row) to port j (column) per hour.

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	82	98	152	102	138	55	121	43	153	54	87	43
1	99	0	85	111	80	105	40	103	34	111	31	64	41
2	119	77	0	128	73	111	40	99	37	99	33	73	35
3	135	96	106	0	107	159	42	129	50	125	53	82	44
4	124	75	75	125	0	124	41	132	40	107	38	71	37
5	114	90	97	151	79	0	48	126	49	149	44	97	47
6	84	59	63	93	56	89	0	93	27	76	26	55	29
7	145	95	91	134	93	143	46	0	52	145	50	89	53
8	94	54	55	75	59	90	31	91	0	84	26	48	29
9	139	94	94	159	88	128	44	136	50	0	41	70	48
10	76	56	58	85	60	73	28	80	29	75	0	53	26
11	131	66	76	116	75	109	33	127	37	123	38	0	39
12	77	58	53	81	59	71	30	82	22	79	28	57	0

Table D.2: A selected sample of demand used in the test instances for the FSNDP. The table displays the number of passengers wanting to travel from port i (row) to port j (column) per hour.

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	79	76	181	119	109	60	107	34	135	48	116	55
1	78	0	86	79	93	104	42	95	26	91	29	60	44
2	140	70	0	137	86	142	46	77	45	115	43	56	31
3	186	75	111	0	85	132	38	133	59	150	51	75	35
4	127	75	51	118	0	101	33	122	34	128	28	79	47
5	113	92	95	124	74	0	53	157	56	152	43	77	33
6	72	45	59	110	65	84	0	112	28	73	24	56	33
7	153	100	84	124	75	170	62	0	32	135	39	77	43
8	87	48	55	74	61	69	37	58	0	91	25	64	35
9	95	120	113	182	123	172	43	159	56	0	45	85	44
10	62	53	75	101	53	59	35	82	23	65	0	41	21
11	110	68	85	125	56	150	30	128	28	146	39	0	37
12	98	60	59	83	55	78	33	106	21	58	35	55	0

Appendix E

Test Instance Solutions of the FSNDP

Table E.1: Solutions for selected test instances of the *full* port case of the FSNDP analysis. The table displays the departure frequency for each route, the index in the route for the port where the waiting time incurs, and the routes represented with the numbers associated with the visited ports. The reader is referred to Table 7.1 and Figure 7.1 to see which ports the numbers correspond to. The examples are solutions computed with the demand sample given in Table D.2.

Instance	Freq.	Wait. ind.	Route
Full-Dis-10-6	1	0	[0, 9, 2, 3, 4, 3, 7, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 7, 3, 4, 3, 2, 9, 0]
	1	3	[3, 7, 6, 5, 6, 7, 3, 4, 3]
	1	0	[3, 4, 3, 7, 6, 5, 6, 7, 4, 3]
	1	7	[3, 2, 9, 1, 2, 7, 6, 5, 6, 7, 3, 4, 3]
	1	8	[3, 2, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3]
Full-Dis-20-6	1	0	[0, 9, 2, 3, 4, 3, 7, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 7, 3, 4, 3, 2, 9, 0]
	1	0	[0, 9, 1, 2, 7, 4, 3, 7, 2, 9, 0]
	4	0	[0, 9, 1, 4, 3, 7, 6, 5, 6, 7, 8, 2, 1, 9, 0]
	1	7	[3, 2, 9, 1, 2, 7, 6, 5, 6, 7, 3, 4, 3]
	1	8	[3, 2, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3]
Full-Imp-20-3	3	0	[0, 9, 1, 2, 8, 3, 4, 3, 8, 2, 9, 0]
	3	0	[0, 9, 1, 4, 3, 7, 6, 5, 6, 7, 3, 4, 1, 9, 0]
	3	6	[5, 6, 7, 8, 2, 1, 9, 1, 2, 8, 7, 6, 5]

Continued on next page

Table E.1 – *Continued from previous page*

Instance	**Freq.**	**Wait. ind.**	**Route**
Full-Imp-20-6	2	0	[0, 9, 1, 2, 8, 3, 4, 3, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 8, 3, 4, 3, 8, 2, 9, 0]
	2	0	[0, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3, 2, 9, 0]
	2	0	[0, 9, 2, 3, 4, 3, 7, 6, 5, 6, 7, 8, 2, 1, 9, 0]
	1	8	[3, 2, 1, 9, 2, 3, 4, 7, 5, 6, 7, 3]
	1	8	[3, 2, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3]
Full-Imp-20-9	1	0	[0, 9, 1, 2, 7, 5, 6, 7, 2, 1, 0]
	1	0	[0, 9, 1, 2, 8, 7, 3, 4, 2, 9, 0]
	1	0	[0, 9, 1, 2, 8, 3, 4, 3, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 8, 3, 4, 3, 8, 2, 9, 0]
	2	0	[0, 9, 2, 3, 4, 3, 7, 6, 5, 6, 7, 8, 2, 1, 9, 0]
	1	5	[3, 4, 3, 7, 6, 5, 6, 7, 3]
	1	7	[3, 2, 9, 1, 2, 8, 7, 5, 6, 7, 3, 4, 3]
	1	8	[3, 2, 9, 1, 2, 8, 7, 6, 5, 6, 7, 4, 3]
	1	8	[3, 2, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3]
Full-Imp-30-6	1	0	[0, 9, 1, 2, 8, 3, 4, 3, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 8, 3, 4, 3, 8, 2, 9, 0]
	4	0	[0, 9, 1, 2, 8, 7, 6, 5, 6, 7, 3, 4, 3, 2, 9, 0]
	4	0	[0, 9, 2, 3, 4, 3, 7, 6, 5, 6, 7, 8, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 8, 7, 4, 3, 7, 6, 5, 6, 3, 4, 2, 1, 9, 0]
	1	0	[0, 9, 1, 2, 8, 7, 3, 4, 7, 6, 5, 6, 4, 3, 2, 1, 9, 0]

Appendix F

All Test Instances for C-DAR-FS Demand Analysis

Table F.1: Percentage of met requests and the corresponding average excess service time in minutes for test instances with fleet size 10, the three demand cases, and all allocation options between the fixed schedule and DAR-service.

Instance	**Low**		**Regular**		**High**	
(FS-DAR)	Req, %	ExcT, *min*	Req, %	ExcT, *min*	Req, %	ExcT, *min*
V = 10						
10-0	71.9	20.0	69.2	20.6	34.6	28.6
9-1	70.8	19.9	66.0	20.7	34.7	27.3
8-2	72.4	21.9	62.5	22.8	36.1	25.2
7-3	65.2	22.2	54.2	21.9	34.9	21.0
6-4	71.0	23.7	59.0	23.8	34.9	25.4
5-5	74.8	24.2	62.8	24.6	33.0	28.0
4-6	73.1	25.5	56.5	25.0	33.8	25.6
3-7	78.3	25.8	60.6	25.8	31.9	28.3
2-8	83.9	25.7	65.1	26.3	30.3	30.8
1-9	84.6	26.1	64.8	27.2	27.4	32.7
0-10	85.8	26.4	63.6	28.1	23.8	35.6

Table F.2: Percentage of met requests and the corresponding average excess service time in minutes for test instances with fleet size 20, the three demand cases, and all allocation options between the fixed schedule and DAR-service

Instance	**Low**		**Regular**		**High**	
(FS-DAR)	Req, %	ExcT, *min*	Req, %	ExcT, *min*	Req, %	ExcT, *min*
V = 20						
20-0	84.5	17.0	84.1	17.0	55.8	29.2
19-1	74.8	16.9	73.3	16.7	56.7	24.5
18-2	85.3	17.6	83.6	17.6	58.2	26.8
17-3	86.9	18.0	84.0	17.8	57.2	27.3
16-4	94.3	18.8	92.8	19.1	56.6	29.7
15-5	94.4	17.8	92.2	18.0	56.4	29.2
14-6	94.9	18.3	92.9	18.6	57.0	29.6
13-7	95.5	18.4	92.4	18.8	56.6	29.1
12-8	95.8	18.6	90.9	18.9	55.8	28.6
11-9	98.3	18.1	95.6	19.1	57.5	28.9
10-10	98.6	18.2	95.6	19.4	57.7	29.4
9-11	99.1	18.3	95.8	19.7	57.3	28.6
8-12	99.5	18.1	96.0	20.5	57.2	27.6
7-13	99.7	18.1	93.7	21.2	55.1	26.1
6-14	99.9	17.8	96.1	21.2	56.1	28.1
5-15	99.9	17.1	97.2	21.0	55.4	29.5
4-16	100	16.8	97.2	21.7	55.1	28.5
3-17	100	16.2	98.4	21.2	54.5	29.9
2-18	100	15.6	99.3	20.3	54.0	30.9
1-19	100	15.4	99.5	20.0	51.8	31.9
0-20	100	14.9	99.7	19.6	49.3	32.9

Appendix G

All Test Instances for C-DAR-FS Reduced Ports Analysis

Table G.1: Percentage of met requests and the corresponding average excess service time in minutes for test instances with fleet size 10 and all ferry allocations. The FSNDP is solved for the *full* and *reduced* port case with *regular* demand. For the *reduced* port case, results are displayed for both the *disregarded* and *imposed* minimum required frequency cases. Infeasible FSNDP solutions are marked with "-".

Instance	**Reduced, disreg.**		**Reduced, imposed**		**Full, disreg.**	
(FS-DAR)	Req %	ExcT, *min*	Req %	ExcT, *min*	Req %	ExcT, *min*
V = 10						
10-0	35.0	16.4	38.4	17.7	69.2	20.6
9-1	39.6	19.2	43.8	19.5	66.0	20.7
8-2	42.7	20.8	49.2	21.1	62.5	22.8
7-3	46.9	22.4	54.4	22.1	54.2	21.9
6-4	50.8	23.1	-	-	59.0	23.8
5-5	54.8	24.9	-	-	62.8	24.6
4-6	57.8	25.2	-	-	56.5	25.0
3-7	56.0	26.8	-	-	60.6	25.8
2-8	59.0	26.9	-	-	65.1	26.3
1-9	61.4	28.0	-	-	64.8	27.2
0-10	63.6	28.1	63.6	28.1	63.6	28.1

Table G.2: Percentage of met requests and the corresponding average excess service time in minutes for test instances with fleet size 20 and all ferry allocations. The FSNDP is solved for the *full* and *reduced* port case with *regular* demand. For the *reduced* port case, results are displayed for both the *disregarded* and *imposed* minimum required frequency cases. Infeasible FSNDP solutions are marked with ”-”.

Instance	**Reduced, disreg.**		**Reduced, imposed**		**Full, disreg.**	
(FS-DAR)	Req %	ExcT, *min*	Req %	ExcT, *min*	Req %	ExcT, *min*
V = 20						
20-0	38.4	12.7	38.4	12.7	84.1	17.0
19-1	41.6	15.1	44.0	15.2	73.3	16.7
18-2	47.2	16.6	49.8	17.6	83.6	17.6
17-3	55.3	18.3	55.3	18.3	84.0	17.8
16-4	60.4	19.7	60.4	19.7	92.8	19.1
15-5	65.0	20.3	65.0	20.3	92.2	18.0
14-6	69.0	20.6	70.0	20.8	92.9	18.6
13-7	74.3	21.0	74.3	21.0	92.4	18.8
12-8	77.0	21.1	77.9	21.3	90.9	18.9
11-9	80.8	21.2	82.5	20.9	95.6	19.1
10-10	83.9	21.1	85.5	21.1	95.6	19.4
9-11	86.6	21.2	88.5	20.8	95.8	19.7
8-12	88.6	21.0	91.2	20.5	96.0	20.5
7-13	90.3	21.1	93.3	20.3	93.7	21.2
6-14	92.9	20.8	-	-	96.1	21.2
5-15	94.5	21.1	-	-	97.2	21.0
4-16	95.8	20.8	-	-	97.2	21.7
3-17	96.2	21.5	-	-	98.4	21.2
2-18	97.7	20.9	-	-	99.3	20.3
1-19	99.3	20.2	-	-	99.5	20.0
0-20	99.7	19.6	99.7	19.6	99.7	19.6