Methods for Bathymetry Informed Planning of Archipelago Transport Systems

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Norrköping 2024
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LIU-TEK-LIC 2024
ISBN 978-91-8075-672-3 (pdf), 978-91-8075-671-6 (print)
ISSN 0280–7971
DOI 10.3384/9789180756723
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Cover designed by author using data from Sjöfartsverket and Helcom

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Printed by LiU Tryck, Linköping, Sweden 2024

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Abstract

Archipelagos are rural regions characterized by their distinct geographic layouts with many separated island communities. Water bodies hinder access to community services and make a well-functioning ferry-based public transport system the only feasible means of mass transportation. Both between islands and to connect to the mainland. Maritime environments provide great routing flexibility. However, outdated or imprecise nautical charts can hinder the safe use of such possibilities in commercial traffic.

This thesis develops methods for strategic planning of archipelago transportation systems, enabling the valuation of novel fairways. Contributions are made to the fields of applied optimization and statistical modeling of spatial data considering the distinct features of archipelago environments.

To improve the inference of fairways, a data fusion model for combining traditional bathymetric data and ship trajectory data from the automatic identification system (AIS) for depth inference is developed. It utilizes probabilistic modeling and survival analysis for spatial interpolation of the two qualitatively different sources of information. To handle the large amounts of automatic identification system (AIS) data and the non-stationarity cause by holes (islands) in the model region, a discretized mesh approach is used.

In the second step an optimization model for joint network design and scheduling of ferry public transport, with the capability of evaluating currently unavailable fairways with opening costs. In this study, characteristic features of archipelago ferry networks are identified. These features are then expressed using a modified vehicle routing model with multiple trips. Results show that factors such as traffic requirements, operating costs and fleet composition has a large impact on the value of a fairway.

In summary, the thesis develops methods for inferring novel fairways using the alternate source of information provided by ship trajectory data. To evaluate such fairways, an optimization model for assessing their scheduling value in ferry based public transport systems is developed.
Populärvetenskaplig sammanfattning


Denna avhandling utvecklar metoder för att förbättra den strategiska planering av skärgårdars transportsystem och möjliggöra värdering av nya farleder. Bidrag görs inom tillämpad optimering och rumslig statistisk modellering som tar hänsyn till de särskilda egenskaperna skärgårdsmiljöer besitter.

För att förbättra skattningen av farleder utvecklas en datafusionsmodell som kombinerar traditionella djupdata med fartygstrajektorier från Automatic Identification System (AIS). Probabilistisk modellering och överlevnadsanalyser används för rumslig interpolering av de två kvalitativt olika informationskällorna. För att hantera de stora datamängderna i AIS-datat och icke-stationäriteten som introduceras av häl (öar) i studieområdet används en diskretiserad modelleringssats.

I det andra steget utvecklas en optimeringsmodell för kombinerad nätverksdesign och schemaläggning av färjetrafiken. Modellen, som baseras på en modifierad ruttplaneringsmodell med flera resor, inkluderar många av de karakteristiska drag för skärgårdstrafik som identifierats och erbjuder möjlighet att utvärdera för närvarande otillgängliga korridorer med fasta öppningskostnader. Resultaten visar att faktorer såsom trafikeringskrav, driftskostnader och fordonsflottans sammansättning bör tas i beaktande vid värdering av nya farleder.

Sammanfattningsvis pekar avhandlingen på hur förbättrad djupinformation kan hjälpa till att härleda möjliga transportkorridorer som inte finns med i sjökorten. Den presenterar vidare en metod för inferens av sådana farleder baserad på faktiska fartygstrajektorier och utvecklar i nästa steg en optimeringsmodell som i ett helhetsgrepp bedömer deras värde i kollektivtrafiksystemet.
Acknowledgments

This work has been carried out at the Division of Communications and Transport Systems (KTS) at Linköping University and the Swedish National Road and Transport Research Institute (VTI). Financing was provided by the Swedish Transport Administration (Trafikverket) via the Swedish Maritime Administration (Sjöfartsverket) under grant TRV 2019/119584.

I want to thank my family and friends for (nearly) always being supportive of my endeavors. And at times providing the right amounts of justified resistance.

To my colleagues at both VTI and Linköping University, who have been crucial in many regards — as company during fika breaks, traveling companions to conferences and as a source of motivation to strive and improve.

Research (and even more so learning to do research) does not always progress in a straightforward manner devoid of frustrations. I want to thank both my supervisors, Gunnar Flötteröd och Tomas Lidén for their kind and continuing support throughout the various stages of this process. I look forward to its continuation.

Stockholm, 2024
Michael Sederlin
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Chapter 1

Introduction


Chapter 1. Introduction

1.1 Background and Context

1.1.1 Archipelagos

Archipelagos are rural communities with distinct characteristics separating them from other rural communities and motivate special care and consideration. The placement of community services such as schools, medical centers and stores is directly connected to the population distributed across the islands separated by water bodies. The distinct geographic layout of archipelagos, with numerous islands in close proximity, offers great routing flexibility for transport and allows many different paths to be used. However, the safe use of such paths for public transport and other commercial traffic relies on accurate depth information for fairways.

1.1.2 Depth Surveying

Navigation and route planning in maritime environments depend on nautical chart accuracy to determine fairways and detect potential hazards. Such charts are often based on data of uncertain quality collected with manual means and outdated positioning technologies (Sjöfartsverket, 2021). Modern methods for nautical surveying rely on single- or multi-beam sonar to create high-resolution point clouds and achieve an accurate and detailed view of the ocean floor (Wiberg et al., 2018). As of 2018, less than 5 % of the Swedish shallow water areas, such as archipelagos and near-coastal areas, had been surveyed with modern methods. Efforts to improve near-coastal naval charts have hence been taken by the Swedish Maritime Administration in cooperation with other actors (Wiberg et al., 2018). Data collection campaigns are subject to several capacity and funding constraints including the following:

(i) Data collection capacity — Measurement capacity caused by a limitation in the number of ships with appropriate equipment available and the availability of competent staff;

(ii) Data quality time window — Factors such as weather, ice growth and the amount of algae can have large impacts on the quality of collected data;

(iii) Data processing capacity — The data processing pipeline has
1.1.3 Public Transport in Archipelagos

Public transport serves an important role in archipelago communities, connecting islands to each other and the mainland. The lack of land-based infrastructure limits the usefulness of private cars, which are often the default mode in rural communities (Makkonen et al., 2013). While private boats are an alternative, ferry-based public transport systems are the only feasible means of mass transportation. Such a strong dependence on the public transport system is not typically seen in rural communities and places high demands on its performance and reliability. The public transport serving in the Gothenburg archipelago provides an illustrative example of such a system. It connects a collection of inhabited islands with each other and the larger city as shown in Figure 1.1 using a combination of fixed and flexible lines. Similar systems can be found in, for example, Auckland, Hong Kong, Seattle, Stockholm and Oslo (Cheemakurthy et al., 2017). Defining features are a combination of fixed and flexible scheduling, an irregular line structure with high variability in the stopping patterns and departure frequencies within each line. While the supply is higher during peak hours, no clear operating cycles with regular departure frequencies can be identified. In addition, the vehicle

several limitations in capacity leading to long lead times between data collection and the availability of updated nautical charts;

(iv) Funding availability — The Swedish maritime administration, in charge of most bathymetric data collection, operates on a business-like model where fairway fees finance their upkeep. The absence of a clear financing structure means that areas outside of the major shipping lanes are not regularly surveyed (Sjöfartsverket, 2019);

To prioritize survey efforts, the Canadian Hydrographic Service developed a model based national priority planning tool focusing on the most used fairways (Chénier et al., 2018). A focus on surveying transport corridors rather than contained geographic areas may result in more efficient use of surveying resources (Chénier et al., 2017). Regular collection of data is expected to benefit many actors ranging from environmental organizations, land owners, municipalities, and local businesses to public transport agencies and operators (Wiberg et al., 2018).
fleet consists of vehicles with different passenger capacities, speeds and onboard amenities.

Figure 1.1: Ferry public transport system operating in the Gothenburg Archipelago (© Styrsöbolaget)

1.1.4 Transport System Planning

Systems planning for public transport is often separated into three stages, given in Figure 1.2, defined by the considerations they cover (Desaulniers and Hickman, 2007). Strategic planning models relate to long-term decisions affecting the structure of a system. In the context of public transport systems planning, strategic planning relates to the design of the network and construction of routes. Tactical level planning concerns topics such as scheduling of services on a given network and set of routes. Such topics may be covered in strategic planning as well. However, the tactical level contains a more detailed analysis and is performed with a higher frequency. Tactical planning typically operates on a within-year time scale. At the operational
planning level, the practical implementation of a schedule is considered. This entails questions such as which vehicles should operate which trips, and how the crew and maintenance should be scheduled.

Figure 1.2: Planning levels and their decisions as described by Desaulniers and Hickman (2007)

The connection between different planning levels is complex. A theme of the work contained in this thesis is the dependency between many planning decisions and the need for considering these jointly. Desaulniers and Hickman detail the relationship between the tactical and operational planning of a bus network, as shown in black in Figure 1.3, as a sequential process across the planning levels. The addition of strategic planning in red has been made by the author of this thesis. While the steps contained in any one planning level are not independent of the others, the distinction may still be beneficial given that they each pose different requirements on the tools used. Considering them jointly at a high enough level of detail may be computationally impossible. In addition, the data required for one planning level may not be available when it is necessary to perform it.
Chapter 1. Introduction

1.2 Objectives and Research Questions

The primary objective of this thesis is to develop methods to optimize archipelago transportation systems with a focus nautical chart accu-
racy and ferry network design considering new or alternate fairways. This aims to improve the strategic planning and operational efficiency in archipelago environments.

To fulfill the primary objective, the following research questions are devised:

RQ-1 **How can ship trajectory data be used in the planning of a water-based transportation system?**
While bathymetry data provides the main information about the depth, other sources of information may provide added insights. This question asks how ship trajectory data from the Automatic Identification System (AIS) can be used to improve depth prediction and, by extension, the inference of fairways.

RQ-2 **How can the archipelago setting be translated to an operations research network design problem?**
Archipelagos have their own distinct characteristics that both pose challenges and create opportunities to manage when planning the transport system. This question asks what these characteristics are and how they can be included in a mathematical model for designing and scheduling such a system.

RQ-3 **How can bathymetric information inform the ferry network design process?**
Given the critical role of water depth (bathymetry) in defining useable links in a maritime transport network in areas of shallow water. This question asks how depth information can influence the network design process and seeks to identify attractive routes for improved depth knowledge.

1.3 **Scope**

This thesis explores the field of mathematical modeling of archipelagos with a focus on optimization and statistical spatial modeling. The detailed scope is defined in relation to:

(i) Geographic limitations — The research in this thesis is limited to archipelago environments, and only concerns water-based transportation networks.

(ii) Spatial modeling — The spatial modeling research contained in this thesis is restricted to a Bayesian framework. The data
Chapter 1. Introduction

used is restricted to traditional bathymetry measurements and ship trajectory data.

(iii) **Network design and scheduling** — The joint network design and scheduling in this thesis concerns fixed scheduling of ferry-based public transport systems, with specific care given to the characteristics of archipelagos. It does not attempt to handle demand responsive traffic components, despite their propensity in such areas. In addition, the present work does not attempt to handle passenger costs, vehicle or berth capacities, line planning or crew scheduling and does not handle demand due to the lack of available data.

(iv) **Planning level** — The work in this thesis pertains primarily to strategic planning for long term development of the transport system. However, a strength of the developed methods is that they also consider tactical level planning decisions.

1.4 Thesis Structure

The rest of this thesis is structured as follows;

Chapter 2 covers statistical modeling of spatial data, with a focus on Bayesian modeling and approximation methods for large data and non-continuous domains.

Chapter 3 introduces the field of optimization modeling for strategic planning, with a focus on integer programming models. It then covers a description of the network design problem, with special attention given to applications on ferry networks.

In the final chapter of the thesis, Chapter 4, the included papers are summarized along with the research contributions and their relations to the proposed research questions. Concluding remarks and suggestions for future research are given.
Chapter 2
Spatial Data Analysis
Chapter 2. Spatial Data Analysis

The work in this thesis concerning statistical modeling of spatial data relies on Bayesian methods for inferring navigable corridors. A data fusion model for combining traditional depth observations and trajectory data from the automatic identification system (AIS) system used for tracking ship movements is proposed. This chapter establishes the methodological foundations for spatial data modeling, Bayesian principles and discretized approximation methods for spatial interpolation with attractive properties for the use case in question.

2.1 Statistical Modeling of Spatial Data

In any form of data modeling, it is crucial to account for the relation between observations. At one extreme, we might assume that samples are independent such that the result of one observation does not influence or predict the outcome of others. However, such an assumption is often an oversimplification of reality. For instance, in time series data, we may expect a stronger connection between values closer in time than those that are more distant. The correlation between the two values is expected to decrease as the interval between them increases. A similar principle applies to spatial data, where the concept is encapsulated in what is commonly referred to as Tobler’s 1st law of geography;

\[
\text{everything is related to everything else, but near things are more related than distant things (Tobler, 1970, p. 236)}
\]

Spatial data modeling explicitly incorporates this assumption for prediction and interpolation.

One of the most prevalent approaches to statistical interpolation of spatial data is Kriging. In computational science and machine learning domains, the same model is commonly referred to as Gaussian Process (GP) regression (Rasmussen and Williams, 2006). It is a geostatistical method where data is modeled as a random process that is continuously indexed over space such that values for all locations are defined in the resulting distribution (Cressie, 1993).

To introduce GP regression more formally, let \( \mathbf{y} = (y_1, \ldots, y_n)^T \) be a vector of values associated with the locations \( \mathbf{s} = (s_1, \ldots, s_n)^T \). Assume that observations exist for the first \( m \) locations such that \( \mathbf{y}_o = (y_1, \ldots, y_m)^T \) are observed at locations \( \mathbf{s}_o \) and \( \mathbf{y}_p = (y_{m+1}, \ldots, y_n)^T \) are to be predicted for locations \( \mathbf{s}_p \). Figure 2.1 shows a concrete
2.1. Statistical Modeling of Spatial Data

instance of a GP with five locations where observations exist for the first three (grey) and values are to be predicted for two other locations (white).

\[ \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \sim \mathcal{N} \left( \begin{bmatrix} \mu(s_1) \\ \vdots \\ \mu(s_n) \end{bmatrix}, \begin{bmatrix} k(s_1, s_1) & \cdots & k(s_1, s_n) \\ \vdots & \ddots & \vdots \\ k(s_n, s_1) & \cdots & k(s_n, s_n) \end{bmatrix} \right), \quad (2.1) \]

where \( \mu(s_i) \) is some mean function and \( k(s_i, s_j) \) a covariance function. It is common for the covariance function to depend on the distance between locations. To make predictions at \( s_p \), a weighted combination of observed values is made, where the weights are determined by the covariance between the observed and unobserved locations as

\[ \begin{aligned}
E [y_p | y_o] &= \mu(s_p) + k(s_p, s_o)k(s_o, s_o)^{-1}(y_o - \mu(s_o)) \quad (2.2) \\
\text{Cov}(y_p | y_o) &= k(s_p, s_p) - k(s_p, s_o)k(s_o, s_o)^{-1}k(s_o, s_p), \quad (2.3)
\end{aligned} \]

such that observations closer to the location being predicted are given more weight in the prediction. Needing to compute the inverse \( k(s_o, s_o) \) which is an \( n \times n \) matrix, where \( n \) is the size of the data, means that GP regression has a prohibitive computational complexity of \( O(n^3) \) (Rasmussen and Williams, 2006).
A valid covariance function $k(s_i, s_j)$ must produce a positive semi-definite matrix. The Matérn covariance function where the covariance between locations $s_i$ and $s_j$ is is one such function that is very common in spatial modeling (Stein, 1999). One formulation of the Matérn covariance function is parametrized by the three parameters $\nu$, $\kappa$ and the standard deviation $\sigma$. Figures 2.2, 2.3 and 2.4 show how the parameters $\nu$ and $\kappa$ affect the strength of the spatial correlation between locations and the impact this has on the resulting gaussian fields (GF). An attractive property is its ability to represent fields of varying degrees of smoothness and capture both small-scale and large-scale variations.

![Figure 2.2: Instances of the Matérn correlation function for different $(\kappa, \nu)$](image)

![Figure 2.3: 2D GF realizations with Matérn correlation function for $\sigma = 1$, $\nu = (0.5, 1.5, 2.5)$ and $\kappa = 1.5$](image)
The Matérn function only relies on the Euclidean distance between locations \( s_i \) and \( s_j \) and is, therefore, invariant to both translation and rotation. This property where the correlation structure does not change across space is known as second-order stationarity (Cressie and Moores, 2021) and affects the applicability of the model in non-continuous regions as archipelagos with islands or where the Euclidean distance is not a good representative of the correlation propagation. It has been shown that naively using non-Euclidean distance metrics can result in invalid covariance matrices (Curriero, 2006). Examples of this are uses of Kriging in estuaries, where the water-based distance is used (Little et al., 1997), or road-based distances in network applications (Ver Hoef, 2018).

2.2 Bayesian Modeling

Statistical modeling attempts to uncover some insights from observed data. This process commonly involves constructing a model characterized by some parameters. In a frequentist approach, these parameters are viewed as inherently deterministic with uncertainty stemming from non-exhaustive observations. A Bayesian framework views the parameters themselves as uncertain and models this uncertainty explicitly through probability distributions (Gelman et al., 2014).

Letting \( \theta \) denote the model parameters and \( y \) the data, we start with the joint distribution \( p(y, \theta) \). From Bayes theorem, the conditional probability of \( \theta \) (the parameters) given that \( y \) has occurred (observations have been made) can be formulated as

\[
p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)} \tag{2.4}
\]
Constructing the conditional posterior distribution constitutes learning from the data, and we can extract any statistics of interest from $p(\theta|y)$. The distribution $p(y|\theta)$ models the probability of the data $y$ given parameters $\theta$ and has several names. It is often referred to as the likelihood function of $\theta$. It is also often known as the data model or the observation model as it expresses the probability of making certain observations given a parameter set $\theta$. The probability $p(\theta)$ is known as the prior distribution over $\theta$ and typically represents beliefs about $\theta$ before seeing any data. Such beliefs can come from previous knowledge about the phenomenon, such as travel times being positive real values within a certain range or the expected precision of a sensor. Figure 2.5 shows the relationship between the prior distribution, the likelihood and the conditional posterior of $\theta$. The likelihood $p(y|\theta)$ is not a probability distribution over $\theta$, and is scaled for visualization purposes in this figure. One interpretation of this is that the prior distribution is weighted so that parameter values which increase the probability of the observations are more likely in the posterior.

![Figure 2.5](image_url)  
**Figure 2.5:** Plot showing the prior, likelihood and posterior distributions.

Often, the primary interest is not on the model parameters $\theta$, but rather on making predictions on $\hat{y}$ based on the observations $y$. The
Bayesian Modeling

**predictive posterior** $p(\hat{y}|y)$ is formed as

$$p(\hat{y}|y) = \int p(\hat{y}, \theta|y)d\theta = \int p(\hat{y} | \theta)p(\theta|y)d\theta \quad (2.5)$$

and integrates over all values of $\theta$ weighted by their probability given the data through $p(\theta|y)$. To place the GP for spatial modeling described in Section 2.1 in a Bayesian context, we can view the multivariate Gaussian

$$\mathcal{N}(\mu(s_i), k(s_i, s_j)) \quad (2.6)$$

as a prior over all possible spatial fields described by parametric mean and covariance functions. The prior contains believed properties of the spatial field such as its mean, range of correlation, smoothness and overall variability prior to seeing the data. The predictive posterior evaluates to

**Hierarchical Bayesian Models / Generalized Linear Models**

A single level model may not adequately represent the phenomenon of interest and a multi-level or **hierarchical** formulation may be preferred. Consider the following example where a spatial field cannot be observed directly. The hidden (latent) field is described with the linear model

$$\mu(s_i) = \beta_0 + \sum_j \beta_j x_{ij} + u(s_i) + \varepsilon(s_i) \quad (2.7)$$

$\mu(s_i)$ is the mean of the field at location $s_i$, $\beta_j$ is the coefficient of covariate $x_{ij}$ associated with location $i$. In the context of depth inference, these covariates could be for example the distance from shore, some qualitative information about the sea bed or other information that might assist in predicting the depth at a location. $u(s_i)$ is an error term capturing spatially correlated noise using, for example, a GP as described previously. $\varepsilon(s_i)$ captures spatially uncorrelated noise. In the example, the coefficients $\beta$ are also represented using appropriate probability distributions. Figure 2.6 shows a graphical model for a hierarchical model with observed variables in grey circles, latent variables in white and parameters as standalone symbols.
Chapter 2. Spatial Data Analysis

Observations are emitted with a probability determined by the observation probability \( p(y_i | \mu(s_i), \sigma_y) \), conditional on the latent field \( \mu(s_i) \). This thesis develops a hierarchical Bayesian model for inference of navigable maritime corridors through a combination of two different observation models. One modeling unbiased observations with some measurement noise using Gaussian distribution with mean \( \mu(s_i) \) and standard deviation \( \sigma_y \). The other likelihood model considers draught values in ship trajectories as censored observations of the depth in a survival modeling framework. Through appropriate variable transformations, a lognormal survival function can be used to express the probability of the true depth exceeding this observed draught. Figure 2.7 shows the relationship between the draught as an observation of the minimum depth and the true depth at a location. The hierarchical Bayesian model allows for the incorporation of both these likelihood models and the spatial field model in a single framework.

**Figure 2.6:** Hierarchical model for a generalized linear model

**Figure 2.7:** The relationship between depth observations and draught observations as censored observations of the true depth
2.3 Approximate Inference of Spatial Fields

Given the possible size of both trajectory data and available bathymetric data, the computational complexity of GP regression is a concern. The existence of islands in the study region means that the Euclidean distance is not the most suitable distance metric to determine the similarity at two locations. Methods exist for reducing the computational complexity of GP that rely on subsampling of the data (Banerjee et al., 2004; Pardo-Igúzquiza and Dowd, 1997), spectral methods (Stein, 1999), dimensionality reduction through clustering (Banerjee et al., 2004) and discretized approximations on lattices (Rue and Tjelmeland, 2002; Hartman and Hössjer, 2008). The spatial modeling in this thesis relies on lattice methods, such as the gaussian markov random fields (GMFR) suggested by Rue and Tjelmeland (2002) that were initially limited to regular grids like the one shown in Figure 2.8 with a Markov dependency structure such that each node depends on the value of its neighbor. A structure which leads to the distribution having a sparse inverse covariance matrix (precision matrix) (Banerjee et al., 2004) that can be exploited for efficient computation.

![Figure 2.8: Extended grid model centered at n₀₀](image)

To use these properties for inference of continuous Gaussian fields,
Lindgren et al. (2011) show how GMFR defined on irregular lattices can approximate a Matérn field. Linear basis functions were used to interpolate between the vertices forming a triangular mesh. The full proof for this connection relies on stochastic partial differential equations (SPDE) and is outside of the scope of this thesis. The SPDE-GMFR method allows for directly producing the sparse precision matrices of a GMFR and using this discrete distribution to perform approximate inference of continuous spatial fields with a Matérn covariance function. Figure 2.9 shows an example of a coarse triangular discretization of an archipelago area with varying resolution where the interior of the islands and exterior of the region of interest are kept coarse to reduce the number of vertices.

![Triangular mesh of archipelago study region](image)

**Figure 2.9:** Triangular mesh of archipelago study region

The SPDE-GMFR approach is implemented in R using the library R-INLA (Virgilio, 2020).
Chapter 3

Strategic Planning Models
This chapter sets the foundation for the work done in routing and scheduling of archipelago public transport systems. It presents an overview of general optimization modeling, emphasizing linear and integer models, followed by an overview of service network design and relevant modeling approaches.

### 3.1 Optimization

Optimization problems appear in many areas of science, engineering and everyday life. At its core, an optimization problem seeks to find the best solution to a problem given a set of constraining conditions, where the notion of best is expressed through some cost function that ranks solutions. We might want to find the most cost-effective way of transporting passengers or goods between locations by finding routes that minimize fuel consumption or travel time.

Mathematically, an optimization problem with constraints can be expressed as:

\[
\text{minimize} \quad f(x) \quad \text{(3.1)} \\
\text{subject to:} \quad g_i(x) \geq b_i, \quad i = 1, \ldots, m \quad \text{(3.2)} \\
\quad h_j(x) = c_j, \quad j = 1, \ldots, p \quad \text{(3.3)}
\]

The decision variable \( x \) is adjusted to find the best solution. It can represent a wide range of decisions such as which arcs to use in a network, the quantities of some cargo to transport or the vehicles to include in a vehicle fleet. The functions \( g_i(x) \) form inequality constraints and \( h_j(x) \) form equality constraints restricting the feasible values of \( x \). The inequality constraints provide lower bounds on feasible values and can be used to model restrictions such as the lowest number of visits at a port or to determine whether a trip has finished within a given time frame. Equality constraints model restrictions that must be satisfied exactly. This could be requirements that a service makes a given number of trips or that ensures flow conservation at nodes in a network. An optimal solution \( x^* \) in a minimization problem is one where the function \( f(x) \) obtains its smallest value in the feasible range.

In this formulation, the objective function \( f(x) \), inequality constraints \( g_i(x) \) and the equality constraints \( h_j(x) \) can assume any functional form. It is common to differentiate between linear, and non-linear optimization problems as they each possess distinct properties and typically require different solution methods.
3.1. Optimization

Linear programming (LP) constitutes a subset of optimization models where the $f()$, $g_i()$ and $h()$ are all linear functions. The strength of LP lies in the fact that whenever a model can be described using only linear functions, there are very efficient algorithms that can obtain provably optimal solutions. Letting $c$ be a vector of cost coefficients and $x$ a vector of variables, a simple LP with inequality constraints can be expressed as:

$$\text{minimize } c^T x \quad (3.4)$$
$$\text{subject to: } Ax \geq b \quad (3.5)$$
$$x \geq 0 \quad (3.6)$$

Linearity guarantees that an optimal solution will be globally optimal.

While standard LP formulations offer many attractive computational properties for optimizing over continuous variables, there exist many instances where this is not sufficiently realistic. The decision of which ship should operate a given route is a binary decision variable, and cannot be represented by fractional values. Similarly, counting variables for trips, stop visits and sometimes cargo quantities requires discrete integer values. To model such cases, it is necessary to consider integer program (IP) or mixed integer-linear program (MIP) models which provide the capability for handling discrete integer or binary variables by extending on the general LP formulation with further constraints on variable values. This is crucial for modeling many problems prevalent in logistics and transportation. It allows for a more realistic representation of real-world scenarios and grows the available toolkit for computational decision support modeling.

Transitioning from a continuous LP formulation to a MIP model introduces computational challenges. Algorithms used for solving continuous LP models typically leverage the fact that optimal solutions will exist at the boundary of the feasible region, considerably reducing the relevant search space (Bertsimas and Tsitsiklis, 1997). No such guarantee exists for MIP models, and the number of potential solutions grows exponentially with the number of variables. This highlights a need for specialized solution algorithms that can manage the added complexity.

Computational capabilities have grown substantially since the first instances of IP decision support models enabling the use of exact methods for increasingly complex problem instances.
To achieve higher degrees of complexity, many researchers therefore choose to rely on heuristic or metaheuristic procedures that provide approximate solutions to the problems.

3.2 (Ferry) Service Network Design

The network design problem is an optimization problem that seeks to develop, or modify, a network $G = (V, A)$ based on some objective.

Research into the transit network design process typically handles the design of service networks, where the routes of the system are constructed (Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009), rather than the physical network. The same is true for maritime network design research such as the liner shipping network design problem where the service offerings are routes to be sailed for cargo shipping (Christiansen et al., 2020; Agarwal and Ergun, 2008; Reinhardt and Pisinger, 2012; Fagerholt, 2004) and tramp shipping network design (Norstad et al., 2011; Gao and Sun, 2023).

Early research into the transit network design problem studied methods to develop bus networks. Given an existing transit service, one can expect that the improvements of redesigning the network, rather than focusing on other more incremental improvements are large (Ceder and Wilson, 1986). However, evaluating the impacts of redesigning an already existing network, rather than constructing a new network, is a difficult problem.

The ferry network design problem (FNDP) describe approaches to constructing service networks with special consideration to ferry transit systems. A ferry service is defined by its route and stopping pattern as well as the time-table it operates under, and methods to construct such systems should take into account its specific operating circumstances. Kepaptsoglou and Karlaftis (2009) details factors to take into account in the network design process are (i) which decision variables to consider, (ii) the desired network structure, (iii) patterns and characteristics of the demand (iv) operational strategies and (v) other constraints. The approach used to model the network design problem will depend both on these factors, as well as the available data.

While natural connections exist, the FNDP differs from other maritime network design applications in several regards. Firstly, the sailing distances are short with many stops in differing sequences.
Secondly, the ferry networks operate in more geographically complex regions which greatly affect the resolution required in routing decisions. The relationship between uncertain sea depth and the traversability of a fairway, the costs of alleviating these uncertainties, and the particulars of a ferry transport system promote a more holistic approach to what the network design process contains.

3.3 Network Design Modeling Approaches

Applying mathematical optimization to the network design problem requires consideration when deciding which modeling approach to use and how to then solve the model. While the work in this thesis has relied on exact solution methods, a large portion of the research literature on FNDP relies on heuristic and meta-heuristic methods to obtain solutions within a reasonable time-frame such as (Lai and Lo, 2004; An and Lo, 2014; Chu et al., 2020). Where heuristic procedures are constructed with a specific problem in mind, metaheuristics are general in form and applicable to many different problems (Hillier and Lieberman, 2010).

Solution bounds provide important information about the quality of an obtained solution. In MIP models, the optimality gap tells us about the distance between the objective value of the best integer solution found and the theoretically best solution at a given stage which provides a bound on the objective value. It is computed as

$$GAP = \frac{|OBJ\ VAL - OBJ\ BOUND|}{|OBJ\ VAL|}$$

where the objective bound can often be obtained by disregarding integer constraints and solving an easier relaxed LP version of the model. The optimality gap is available for exact methods but is typically difficult, and sometimes impossible, to obtain for heuristic procedures. As a consequence, it may not be possible to know how close to the optimum a solution is when such methods are used.

Heuristics & Meta-Heuristics

There are many heuristic and meta-heuristic procedures available to obtain solutions from a wide variety of optimization models. This section details a small subset of these that are found in the reviewed literature on the FNDP.
Chapter 3. Strategic Planning Models

Multi-stage procedures leverage the problem structure to decompose it into subproblems that can be solved sequentially using appropriate methods that were not available for the full problem. Since the true dependency between decisions typically is not sequential, such approaches will not find a globally optimal solution. In a multi-stage approach, the subproblems may be solved exactly or using a combination of procedures involving other heuristics or metaheuristics.

Genetic Algorithms emulate an evolutionary process where a population of trial solutions is allowed to generate new trial solutions based on their fitness scores. This process continues until the stopping criteria have been reached. For example, if no improvement has been achieved in a given number of iterations (Hillier and Lieberman, 2010).

The Variable Neighborhood Search relies on the notion of not searching the entire solution space at once, but rather in local neighborhoods around an incumbent solution. This is done in an iterative manner where the best neighborhood is selected to continue the search until no improvement can be made. The variable neighborhood search (VNS) is an attractive meta-heuristic for problems with a large solution space, and in non-linear problems, as the search over multiple neighborhoods reduces the risk of getting stuck in a local optima (Gendreau and Potvin, 2010).

3.3.1 The vehicle routing problem

The vehicle routing problem (VRP) is an integral problem archetype in optimization modeling that can be seen as a generalization of the traveling salesman problem (TSP). Where the traditional TSP answers the question of which order vertices in a network should be visited such that the total cost is minimized, the VRP also assigns vehicles to these "customers". It is relatively simpler than the pickup and delivery problem (PDP) as demand is only represented by a single visit, rather than an origin-destination pairing. The VRP was first proposed by Dantzig and Ramser to model the optimal shipments of gasoline from a single terminal to multiple stations (1959). Applied extensions of the VRP have been used successfully in maritime planning. For example by Reinhardt and Pisinger to optimize container shipping (2012) and by Fauske et al. to schedule periodic maritime surveillance operations (2020). Figure 3.1 shows a single instance of a VRP where several...
3.3.1 The vehicle routing problem

vehicles start at a terminal, make trips such that all customers are visited by a vehicle and return to the terminal.

![Diagram of a VRP model with three ferries and islands visiting all stops and returning to the terminal.]

**Figure 3.1:** A single instance of a VRP model with three ferries islands visiting all stops and returning to the terminal.

In order for a route to be a valid solution in a VRP, it must not contain any subtours. A subtour is a route that does not visit all required vertices. In the context of Figure 3.1, an invalid subtour could start at \( s_5 \), visit \( s_6, s_1 \) and finally return to \( s_5 \). Using subtour elimination constraints to ensure their absence adds substantially to the computational complexity of the model as they grow exponentially in number with the number of vertices in the network (Toth and Vigo, 2002). To reduce the complexity, techniques allowing subtour elimination constraints to be omitted exist. For example, by using a time-expanded graph where it is not possible to return to already visited vertices (see Fauske et al., 2020), or by carefully selecting the arcs available when constructing the route such that subtours cannot be created (see Reinhardt and Pisinger, 2012).
Chapter 3. Strategic Planning Models

To extend a problem archetype like the VRP, problem specific auxiliary constraints are added. There are now many different implementations of this model form in different areas of application. Important extensions developed the ability to handle temporal decision variables and a fleet of vehicles with different properties. A prevalent trend in the literature is towards a higher degree of complexity and realism (Mor and Speranza, 2022). Including temporal considerations in the formulation is crucial in many domain applications such as travel demand in a transit problem or the time for visiting a port in a cargo shipping application. Developments into the VRP have included the handling of time window constraints which further restrict the visits to specified periods. Such constraints have been placed on both stop visits and the arcs in the network and may affect departure and arrival times in the solutions, but are model inputs and do not constitute actual decisions in the model. Figure 3.2 shows the time window requirement \( w \) for a single stop and how the trips with visits within this interval work towards satisfying it. An instance of time constraints on the arcs was studied by Lysgaard (1992) who performed vehicle routing and scheduling of a truck fleet where certain arcs consisted of ferry connections between islands.

![Constraint window](image)

**Figure 3.2:** Time window requirement for several trips visiting a single stop in the VRP. Trips in red do not contribute to the constraint fulfillment as their stop visits occur outside of the constraint window bounds.
3.3.1 The vehicle routing problem

The Multiple Trip Vehicle Routing Problem

In the first iterations of the VRP, vehicles were restricted to only perform a single journey during the planning period, making the distinction between a vehicle and a route unnecessary (Mor and Speranza, 2022). The multiple trip vehicle routing problem (MTVRP) extends the traditional VRP to allow vehicles in the fleet to make several trips that start and end at a depot during a single scheduling period. Cattaruzza et al. (2016) presents a thorough review of model formulations and applications of the MTVRP. Like the traditional VRP, the MTVRP works on a (directed or undirected) graphs and determines the arcs used in a solution such that the demand at the vertices is satisfied. To account for multiple trips, the standard VRP is expanded with an index for the trip $r$ for the arcs and stops making the problem larger and more difficult to solve. To achieve a proper separation between trips when multiple trips are allowed, a representation of their start and end times is necessary. This is typically done by introducing a new variable $t^r_i$ representing the time a trip visits stop $i$, where $t^r_0$ represents the trip start and $t^r_{N+1}$ represents its finishing time.
Chapter 4

This Thesis
4.1 Summary of Papers I and II

Paper I: Estimation of near-coastal bathymetry using AIS ship movements

In near coastal environments, nautical charts provide crucial information for navigation and routing both in real-time operations and during planning stages. The cost of data collection as well as capacity constraints in the processing pipeline make reliable bathymetric information in such areas sparse. Prioritization rules can help guide the efforts to where information is the most valuable. Ship trajectory data from the Automatic Identification System (AIS) provide accounts of real ship movements, indicating both desirable paths and minimum depths. Paper I presents a statistical model for combining sparse bathymetric soundings with AIS observations for improved prediction of depths for generation of feasible transportation corridors. The method relies on viewing AIS draughts as censored observations of the true depth and uses methods from geostatistics, Bayesian modeling and survival analysis. A case-study is performed for the southern archipelago of Gothenburg using the program R-INLA. The non-stationarity caused by having boundaries with known (zero) depth and holes (land) in the domain is handled through discretization. Varying amounts of AIS data, ranging from none to 1824 observations, are used in the experiments. Results show predicted depths within the range of data values, and that inclusion of AIS data serve to push the field down to ensure that traversable areas are predicted as such revealing corridors in narrow passages where bathymetric soundings are lacking.

Research contributions

Paper I makes three research contributions.

(i) It creates the ability to include AIS data in naval charting and navigation, taking the uncertainties in either data source into account explicitly.

(ii) A new measurement equation for the inclusion of AIS data in statistical sea depth modeling is developed.

(iii) Factors relevant to the application of the method are identified through a large case study using real data.

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4.1. Summary of Papers I and II

Research Questions

Paper I contributes to the fulfillment of research question RQ-1 relating to the use of alternative data sources in depth estimation, in particular trajectory data from AIS.

Co-authorship and contributions of Paper I

Gunnar Flötteröd is a co-author of Paper I and contributed with supervision, method development and writing and editing of the article. The author of this thesis contributed as main author and had the leading role in writing the article as well as developing and implementing the method.

Paper I status

Research contained in Paper I has been presented at:

- The Young Researchers Seminar organized by ECTRi, Lisbon, 2023.
- The World Conference for Transport Research (WCTR), Montreal, July 2023.

Paper I is currently under review in a special issue journal associated with WCTR 2023 after recommendation.

Paper II: Ferry network design and scheduling: A joint approach for analysis of pathway alternatives

Paper II presents an integrated approach for routing and scheduling of ferry systems operating in archipelago environments, taking their distinct geographic circumstances into account by allowing for detailed geographic representation of routes. Archipelago public transport differs from other rural public transport systems in their importance for providing accessibility owing to the lack of other alternative modes. The developed method is an application of a multi-trip vehicle routing model capable of assessing the system scheduling value of incorporating currently unavailable pathways with opening costs. The paper presents thorough validation tests of the implementation as well as scaling
results for the inclusion of window-based traffic requirements and fleet size. Findings from the paper show that the value of modifications to the physical network cannot be assessed in isolation, but must take the schedule, demand patterns and operating circumstances into account.

Research contributions

Paper II makes the following research contributions:

(i) Distinct characteristics of archipelago public transport are identified which previous research has not explicitly addressed.

(ii) A MIP formulation for joint routing and scheduling of archipelago public transport. The model expands the field of ferry network design by combining many aspects of the problem such as complex and irregular stopping patterns and departure frequencies, a varied vehicle fleet and a detailed representation of the physical network with complex routing choices.

(iii) Furthermore, the model allows for transparent evaluation of the scheduling benefits of network modifications.

(iv) The model is implemented and evaluated on a case study of the Gothenburg archipelago.

Research Questions

Paper II contributes to the answering of research questions RQ-2 and RQ-3 relating to the characteristics of archipelago public transport systems and inclusion of bathymetry data into the network design process.

Co-authorship and contributions of Paper II

Paper II was co-authored by Tomas Lidén. Tomas Lidén was responsible for the original work on model development and has contributed with supervision and editing of the article. The author of this thesis contributed with further development of the method and the full implementation of the model as well as generating and analyzing the results. The author of this thesis furthermore served as the main author of Paper II and had the leading role in writing the article.

Paper II status

Research contained in paper II has been presented at
4.2 Concluding Remarks and Directions for Future Research

Archipelagos create the setting for the work in this thesis and a focus on archipelago transport and fairways therein creates the primary connection between the work done in Paper I and Paper II. The methods developed relate to the design and planning of archipelago transport systems with a focus on the interconnectedness between the physical restrictions imposed by water depth, and lack of data thereof, and the evaluation of new fairways in the scheduling and routing of ferry networks. Methodologically, the thesis delves into the fields of Bayesian modeling of spatial data using approximate methods and survival analysis for the inclusion of AIS data in bathymetric modeling, and into routing and scheduling for the design of ferry public transport networks. Previous research into the combination of AIS data and bathymetry is limited and has been restricted to using nautical charts to improve trajectory accuracy in regions of low positioning quality. The methods developed in Paper I instead use AIS trajectory data to improve bathymetric models in regions of low depth data quality. Such information can help in inferring transport corridors and, by extension, extracting information on the usability of new fairways. The methods developed in Paper II, then, allow for evaluating the system benefits of including new fairways in the ferry network design process representing key aspects of archipelago public transport. Such evaluations can provide inputs to survey planning in the case of fairways with uncertain depth conditions, or to the modification of existing routes to improve the efficiency of the system.

Extensions of the network design model

To further use bathymetry data in the network design process, a more detailed approach may be desired. Instead of simply suggesting new
fairways to add to the network, link attributes can be extracted to provide conditions for the use of both novel and existing corridors. Such information could enable operational decisions to be made such as the design of vehicle fleet in favor of vehicles with a lower draught. One may also consider that restrictions on useable transport corridors are not exclusively created by the physical environment in the form of water depth, but may also be imposed by, for example, speed restrictions to protect the shoreline or other environmental concerns.

The model developed in Paper II is a MIP that was solved with exact methods and is shown to be computationally challenging to solve with exact methods for large instances where many window constraints are considered. In order to use the model for real-world strategic planning, as well as enable the inclusion of elements such as demand-responsive services, the solvability of the model must be improved. Future research should therefore focus developing, for example, decomposition methods or heuristics to obtain high quality solutions in a shorter time.

Demand responsive elements are a key characteristic of archipelago transit, and rural transit in general that can cater to the needs of the local population in a more cost-effective manner than fixed routes and schedules. Future research could focus on incorporating such elements into the model developed in Paper II. Such services can be expected to benefit more strongly by detailed bathymetric information both in terms of route planning and vehicle choice to cover the demand. Incorporating such elements would increase the complexity of the model and result in the need to handle stochastic elements such as demand patterns and vehicle availability.

Another interesting extension of the current model formulation would be the inclusion of line planning as a model decision, rather than a given input. This would allow the model to suggest new lines and routes based on changes in traffic requirements and network modifications through the inclusion of new fairways. To do so in a single model might prove difficult and necessitate a multi-stage approach where line planning is performed by a separate higher level model.

Relation to other domains

The methods outlined in this thesis hold potential for application beyond maritime settings. Many of the captured features such as
4.2. Concluding Remarks and Directions for Future Research

Flexible stopping patterns and departure frequencies may also apply to land-based rural transit contexts. An interesting future research direction would therefore be to extend the developed model to additional domains. In addition, the act of evaluating corridors in a routing and scheduling problem has potential outside of archipelago transit. In maritime freight transport, connections are often closed for a myriad of reasons such as groundings and security issues. This is also true for other transport systems such as rail and aviation networks as well as general road transport. A way of applying the concepts to such a problem would be to not consider the value as the cost of opening a new corridor, but rather the benefit of investing in the continued operation of an existing one.
Bibliography


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Abbreviations

FNDP ferry network design problem

LP linear programming

IP integer program

MIP mixed integer-linear program

MTVRP multiple trip vehicle routing problem

VRP vehicle routing problem

TSP traveling salesman problem

PDP pickup and delivery problem

VNS variable neighbor search

GMFR gaussian markov random fields

SPDE stochastic partial differential equations
Bibliography

**GF** gaussian fields

**GP** Gaussian Process

**AIS** automatic identification system
Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789180756723
Methods for Bathymetry Informed Planning of Archipelago Transport Systems

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