Design Performance Index $I_j = \sum_{i=1}^{12} Z_i \times Y_i^{M=E/J/j}$

$Pressure = 0.265 \times area^{-0.57}$
Framework for holistic design of ferries focusing on lightweight ice going hulls

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Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy on Thursday the 29th of September 2022, at 10:00 a.m. in F3, Lindstedtsvägen 26, Stockholm.

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Abstract

Waterborne public transportation (WPT) is slowly increasing in importance as an active component of public transportation networks in cities. City planners are looking at WPT to overcome urban congestion and pollution. However, prevalent challenges like ferry procurement, poor state of existing ferry fleets and technical challenges like the presence of ice, have created reluctance in the minds of public transport providers (PTPs). While contemporary research shows ferries can be economical and environmentally friendly, there are some fundamental challenges that need to be addressed before PTPs can feel confident.

In this regard, deterrents from PTP’s perspective are identified and solutions are investigated, starting with a systematic characterization of WPT. A definite structure for operational requirements is proposed in an objective manner. Using these as basis, two standard ferry sizes that could fulfil multiple WPT roles in majority of cities are introduced. For establishing city-wise tailoring, platform-architecture based modularization of ferries is proposed. The ferry modules are tailored with respect to operational requirements in a clear and objective manner through the introduction of an evaluation methodology. The method incorporates economic, social, environmental, and regulatory stakeholders. These proposed solutions are aimed at improving PTP’s confidence in WPT and provides solutions for the marine industry to produce quick, cost efficient and tailored ferries.

Next, the scope is focused towards investigating sustainable operations in freshwater ice conditions, typically found in the Stockholm region in Sweden. The ice going ferries today operate with ice strengthened heavy hulls. While they work well in ice, they perform poorly in comparison with non-ice going ferries during ice free months. Correspondingly, solutions towards lightweight ice going hulls are investigated.

This investigation starts with understanding ice-hull interaction mechanisms. Then, techniques to estimate the ice loads are investigated. We adopt a probabilistic approach to tackle the limitations due to the stochastic nature of ice and a lack of experimental data. The resulting load cases are used for evaluating lightweight structural concepts.

The investigation is approached by dividing ice-hull interaction into quasi-static, dynamic and abrasive loading phases. Several candidates corresponding to the first two loading phases are investigated parametrically. The range of structural concepts include metal grillages, bio-inspired composites, and sandwich structures. Realistic loading models for quasi-static and impact mechanisms are developed and validated with experiments. The winning candidates for each loading phase are combined to propose a tri-layer lightweight structural concept. Three candidates for the concept are evaluated and compared.

The thesis answers several questions that riddle WPT today. But at the same time, it raises new questions. Several directions for future work are identified. With continued development, it would be possible to see modularly tailored ferries operating with lightweight hulls in WPT systems around the world.
Keywords:

waterborne public transportation, commuter ferry, modular design, platform architecture, operational requirements, sustainable performance index, ice-hull interaction, lightweight ice-going hulls, composite, sandwich structure, ice impact model.
Sammanfattning


Avhandlingen svarar på flera frågor som idag hämmar vattenburen kollektivtrafik. Den väcker samtidigt nya frågor och flera riktningar för framtidiga studier identifieras. Slutsatserna belyser möjligheten för modulärt skräddarsydda färjor med lättviktskrov att operera i den vattenburna kollektivtrafiken runt om i världen.
Nyckelord:
kollektivtrafik på vatten, modulärt färjekoncept, modulär design, plattformsarkitektur, operativa krav index, hållbarhetsparametrar, isbelastning, isförhållanden, isegenskaper, komposit, sandwichstruktur, lättvikts isgående struktuer.
Preface

One of my earliest memories as a child was staring at a cow being milked. It kept me transfixed as I wondered how a creature that ate green grass could produce white milk. At that time, I understood that there is too much mystery that surrounds me, and the best job in the world would be to unravel them. Little did I know that decades later I would be doing my PhD. Has this pursuit quenched my thirst? On the contrary, it has only made me thirstier!

My fascination for naval architecture was quite accidental. It was during an internship in 2009 when I visited Mazagon Docks and witnessed the construction of a stealth frigate. Since then, up till now I have had the privilege to indulge in a variety of topics associated with the subject. This thesis is special to me for it evoked a sense of creativity and wonder, which were my primary motivators.

The research work was performed at the Centre for Naval Architecture, School of Engineering Sciences, KTH Royal Institute of Technology, Sweden. The work was initiated and supervised by Karl Garme, Magnus Burman and Zuheir Barsoum. The research project was financially supported by Trafikverket (Swedish transport administration) and Region Stockholm (Stockholm regional council) for which I express my sincere gratitude.

First, I would like to thank my teacher and supervisor, Karl Garme. Thank you for nudging me towards striving for excellence and being forthcoming whenever I needed help. Next, I would like to thank my co-supervisors Zuheir Barsoum and Magnus Burman for their expertise and guidance in shaping my research in the right direction. I would also like to thank my earliest inspirations who nudged me towards research, Rajiv Sharma.

Next, I would like to express my immense gratitude to my parents, Brig. C S Sreeramulu and Shoba Cheemakurthy. Being parents is a difficult job, one that takes immense responsibility. I was privileged enough to be born in such a house where I was imbued with good virtues and was allowed the freedom to remain curious about the world. Next, I would like to thank my parents in laws, Col. K C Padhy and Gayatri Padhy, for their kind words of encouragement and love. Next, I would like to thank my wife, Shalini Padhy. You have been a constant pillar of support during my research journey. I am grateful for keeping my spirits up and finding joy in life. Finally, I would like to thank my sister Mugdha for being a constant companion since childhood.

Next, I would like to thank my friends at office, Pahansen de Alwis, Meng Zhang and Marion Aku Astine Zu with whom I have shared wonderful conversations over weekly lunches and fikas. You helped me keep my spirits up and advised when I needed help.

Finally, I would like to thank my friends who made me feel at home, despite being continents away. Visakh with whom I spent innumerable fikas discussing and bantering. Shail without whom a lunch break would be incomplete. Sam, Anna, Vishnu, Jason, Olga, Erlend and Benjamin with whom I have laughed countless evenings, played board games and travelled far. I thank them all for making sure I continued to remain sane and being there for me.

Harsha Cheemakurthy
Stockholm, September 2022
Dissertation

The thesis consists of an extended summary and the following appended papers:

**Paper A**


**Paper B**


**Paper C**


**Paper D**


**Paper E**


**Paper F**


**Paper G**


**Publications not included in the thesis:**

**N1**


Division of work between authors

**Paper A**

The principal challenges of WPT were identified during discussions between waterborne public transportation’s stakeholders. The meetings were organized by Garme, and challenges were compiled by Cheemakurthy and Garme. The idea for modularization was developed during discussions between the authors. Cheemakurthy explored platform architecture as a means to achieve modularization and outlined a series of steps to achieve it. Standard hull sizes and energy requirements were calculated by Cheemakurthy under the supervision of Garme. Cheemakurthy wrote the paper under the supervision of Garme.

**Paper B**

The need for a system to facilitate selection of optimal modules for the modular ferry concept was identified during discussions between Cheemakurthy and Garme. The analytic hierarchic process method and its fuzzification methodology was tailored to meet the problem by Cheemakurthy. The corresponding calculations and applications of the method were developed by Cheemakurthy. The paper was written by Cheemakurthy under the supervision of Garme.

**Paper C**

The idea of using sea-ice data to predict freshwater performance was developed by Zhang and Cheemakurthy during discussions with Ehlers and und Polach. Zhang performed calculations for ice loads and conducted FEA simulations. Cheemakurthy collected and processed ice data and contributed to choosing datasets for the probabilistic method. The calculations were verified, and associated uncertainties of the method were identified by Cheemakurthy. The paper was written by Zhang under the supervision of Garme and results were presented by Cheemakurthy at OMAE conference.

**Paper D**

The need for quantifying the uncertainties associated with ice operations was identified during discussions between Cheemakurthy, Zhang, Ehlers and und Polach. Cheemakurthy developed a fish bone structure for contributing factors under the supervision of Ehlers and und Polach. The statistical model was developed by Cheemakurthy. The factors were analysed by Cheemakurthy under the supervision of Garme. The contribution to ice load calculations for input into the model and cross verification of uncertainty calculations were done by Zhang. The paper was written by Cheemakurthy under the supervision of Garme. The results were presented by Zhang at ISOPE conference.

**Paper E**

The motivation towards the need for lightweight ice going hulls was developed during discussions between Cheemakurthy, Barsoum, Burman and Garme. The metal grillages were developed under the supervision of Barsoum. The composites were developed under the supervision of Burman. The development of finite element models and their validation was performed by Cheemakurthy. The analysis of structures was performed by Cheemakurthy.
under the guidance of Barsoum and Garme. Cheemakurthy wrote and edited the manuscript with supervision from Barsoum and Garme.

**Paper F**

The motivation towards the need for lightweight ice going hulls was developed during discussions between Cheemakurthy, Barsoum, Burman and Garme. The metal grillages were developed under the supervision of Barsoum. The composites were developed under the supervision of Burman. The experimental data was made available by Barsoum. The development of impact models and their validation was performed by Cheemakurthy. The analysis of structures was performed by Cheemakurthy under the guidance of Barsoum and Garme. Cheemakurthy wrote and edited the manuscript with supervision from Barsoum and Garme.

**Paper G**

The concept of a tri-layer structural concept was developed by Cheemakurthy in consultation with Garme, Barsoum and Burman. The model for representing impact was developed by Cheemakurthy under the supervision of Barsoum. The model for representing realistic quasi-static loading was developed under the supervision of Garme. The parametric range for composites were chosen under the supervision of Burman. With the help of experimental data sourced by Barsoum, the impact model was validated by Cheemakurthy. The analysis of structures was performed by Cheemakurthy. The draft was written by Cheemakurthy under the supervision of Garme, Barsoum and Burman.
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Chapter 1
Introduction

1.1. Background

Waterborne public transportation (WPT) has been gaining popularity as a viable means of transport. It complements the existing network and shows potential for reducing congestion and urban emissions. While there is some impetus among public transport providers (PTPs) and research showing WPT to be economical, environmentally friendly and sustainable [1, 2], many PTPs still find it cumbersome and experience several adoptive challenges. The challenges are both regulatory as well as technical in nature. The principal technical challenge is the lack of tailored ferry options that are economical and quick to procure. An additional challenge in countries like Sweden is sustainable operations in freshwater ice.

1.2. Research Objectives

The overall aim of the thesis is to explore the development of commuter ferries that are customizable in meeting operational requirements while being easily procurable in terms of cost and time. This could lead to the standardization of ferry designs as part of a sustainable multimodal transport system. Towards the concept’s development, the thesis has two primary objectives. The first objective focuses on the overall concept development for the ferry. The second objective explores the feasibility of a lightweight ice going hull in Nordic WPT conditions.

The research questions for the two objectives can be expressed as,

- Which vessel size and type are the most efficient in the public transport context in relation to function, transportation demand and environmental footprint?
  - Which operational requirements are characteristic of WPT?
  - What are the vessel characteristics that are typical of a WPT ferry?
  - How could typical WPT commuter ferries look like?
  - How can one measure the efficiency of a ferry in meeting operational requirements?
  - How can one improve the accessibility to tailored ferries for PTPs?
1.3. Research Methodology

Considering the wide scope of research objectives, several subject areas including engineering design, transport research, naval architecture, structural mechanics, ice-hull interactions, and statistical methods are studied. A thorough literature survey was the starting point that laid an understanding of the state of the art, associated shortcomings, and its impact on WPT. The research methodology is divided into two parts following the two primary objectives.

![Diagram of research methodology]

**Figure 1:** Research objective 1: Development of a tailored commuter ferry.

The first objective is represented by the black box in Figure 1: development of a tailored commuter ferry. We start by investigating WPT systems globally including ferry types, sizes, capacities, docking infrastructure and routing strategies. Next, we conducted passenger surveys and interviews to understand passenger preferences towards ferry design. Together with discussions with PTPs, researchers and consultants through participation in workshops, a structure for operational requirements describing WPT is developed. With these requirements as basis, ferry concepts including ferry sizes, capacities and speeds are developed using the principles of naval architecture. A platform architecture-based method is developed to modularise the developed ferry concepts and tailored them according to operational requirements. The method’s advantages are explored from the perspective of
achieving cost efficient, procurable, and tailored ferries. The modular ferry concept is explored practically in different operational scenarios to assess its viability.

The earlier developed operational requirements are quantified to assess the ferry’s compliance and performance for a given WPT scenario. For this, multi criteria decision making methods are surveyed and fuzzy analytic hierarchic process (AHP) in combination with extent analysis and particle swarm optimization is chosen. The foundation for objective assessments was criteria quantification. This was achieved with the help of a literature study, passenger surveys and interviews. Several applications of the method are developed including ferry assessment and modular assembly.

The second objective is the development of a lightweight ice going hull suitable for WPT conditions. The process flow is shown in Figure 2. We started by understanding the nature of ice-hull interaction through a literature study and a study visit to Technical University of Hamburg (TUHH). The knowledge gained established the lack of ice load experimental data and limitations of analytical prediction methods for freshwater ice. We started by amassing local ice data from the Swedish Meteorological and Hydrological Institute (SMHI). Using the data, probabilistic and analytical models were explored to predict ice loads on hull structures. The predictions were treated with uncertainty analysis using variation mode and effect analysis (VMEA). The analysis showed a large uncertainty with ice load prediction methods and correspondingly drove us towards choosing a conservative approach to hull design.

Next, we studied the behaviour of a steel hull with (a) inland waterway scantlings (b) ice class scantlings against the loads predicted earlier. The findings are used to motivate the possibility of a lightweight hull panel. A hypothetical panel structure is proposed as a composite of layers capable of sustaining quasi-static loads arising from ice crushing, dynamic loads from impact and spalling and abrasive loads from broken ice scraping. A literature survey is performed to identify suitable structural concepts and materials. Quasi-static investigations are conducted in ANSYS using an FE model validated with data from literature. For dynamic impact investigation, an impact model representing (a) rigid body and (b) ice using cohesive zone method (CZM) elements is used in LS Dyna. The model is validated with experiments conducted at The Hamburg University of Technology (TUHH).
in collaboration with Royal Institute of Technology (KTH). Lightweight candidates are identified among the participants and assembled. This resulted in a proposed lightweight structural concept for the hull. The different structural concepts and materials are assessed from a life cycle perspective for cost, emissions, and energy footprint using data from manufacturers.

1.4 Research Contribution

The thesis is a compilation of all research findings in the form of an extended summary followed by the appended papers: A – G. In paper A, a platform architecture based modular approach is proposed for designing tailored ferries as a solution to address current procurement challenges. In Paper B, a holistic operational requirements structure is developed and used to develop a ferry assessment methodology using fuzzy analytic hierarchic process. In paper C, a probabilistic ice load prediction method is developed for freshwater ice conditions. In paper D, all parameters affecting ice operations are investigated using uncertainty analysis and largest sources of uncertainty are identified. In Paper E, structural concepts (metal grillages, sandwich structures and stiffened sandwich structures) and materials are parametrically investigated for quasi-static ice loading, leading to the identification of suitable candidates. In Paper F structural concepts (metal grillage, fibre reinforced plastic (FRP), metal-FRP, metal-ceramic-viscoelastic) and materials are investigated for ice impact loading, leading to the identification of suitable candidates. In Paper G, a template for lightweight hull structure is proposed according to the three phases of ice-hull interaction. The findings from Paper E-F are combined to propose lightweight hull structural concepts.

Paper A
A modularly tailored commuter ferry platform. [3]

We look at the biggest implementation challenges of WPT and identify various hurdles that affect PTP’s unfavourable perception towards it. The inaccessibility to efficient, quickly manufactured, and inexpensive ferries are argued to be major deterrents. Further, questions on the ferry’s environmental impact, speed and multi-modal integration affecting PTP’s perception are answered. A fundamental drawback being the lack of standard definitions for operational requirements is identified. This was seen to lead to regional differences in ferry metrics that prevent standardization of ferry designs. To overcome this challenge, a framework for standardizing operational scenarios by classifying WPT operational profiles into three standard route types is created. Then a standard operational requirements structure developed in Paper B represents the scope for achieving a standardised WPT fleet. Key design metrics describing a WPT ferry including overall dimensions, capacities, and operational speeds are proposed. Considering these key ferry metrics and defined operational profiles, platform architecture is adopted to propose an efficient and sustainable concept for a modular commuter ferry. Applications of the concept is demonstrated in different operational scenarios.
Paper B
Fuzzy AHP-Based Design Performance Index for Evaluation of Ferries. [4]

A holistic structure to describe operational requirements for WPT is presented. The structure is developed as a three-stage hierarchy that lays down minimum requirements as well as metrics for performance improvements. A novel evaluation methodology is proposed to assess ferries against these operational requirements. The methodology is developed using fuzzy AHP techniques using extent analysis and particle swarm optimization. It converts the PTP’s subjective preferences into a single dimensionless index to facilitate objective decision making. Four applications are envisaged (a) driving tailored design at shipyards, (b) comparison of second-hand ferries, (c) guiding resource allocations during refurbishment and upgrades, and (d) optimizing the assembly of modular ferries.

Paper C
Ice pressure prediction based on the probabilistic method for ice-going vessels in inland waterways. [5]

In this paper, a probabilistic approach to predict freshwater ice pressures based on existing datasets gathered for thin first year ice is presented. Different design strategies are implemented to evaluate the ice-hull interaction load and the influence of ice exposure factors. Ice information, i.e., ice type, thickness, mechanical properties, for Lake Mälaren is extracted and analysed. Ice properties are determined based on empirical formulae and are validated by reference data. Finally, one local design pressure curve which can be used for Lake Mälaren independent of hull dimensions is proposed.

Paper D
Statistical estimation of uncertainties associated with ship operations in freshwater ice. [6]

In this paper, uncertainty arising from different components of an ice operation scenario in estimating the operational time window is evaluated. Variation Mode and Effect Analysis (VMEA) is adopted to calculate the uncertainty. Five primary criteria are identified as ship resistance, structural loads, machinery, ship strength, and operations. Structural loads and ship resistance are found to be leading contributors to uncertainty. Further, sub contributors to uncertainty are identified.

Paper E

In this paper, different structural concepts and materials that can withstand quasi-static ice crushing loads are investigated parametrically. The structural concepts include metal grillages, sandwich structures and stiffened sandwich structures. Several material combinations are investigated. Significant parameters and parametric interactions are identified for each structural concept. Subsequently, parametric trends as well as best cases are identified.
Paper F
Comparison of lightweight structures for impact loads during ice-hull interaction. [8]

In this paper, different structural concepts and materials that can withstand dynamic ice loading represented by ice impact are investigated parametrically. Novel bio-inspired structural arrangements like bouligand FRP composites and ceramic-metal composites are explored along with more traditional concepts like FRP composites and metal grillages. Significant parameters and parametric ranges are identified for each structural concept that may be used in structural weight reduction. Subsequent parametric trends as well as best cases are identified.

Paper G
A lightweight structural concept for freshwater ice going vessel. [9]

In this paper, a template for a lightweight structural concept consisting of layers corresponding to the three ice-hull interaction loading phases is developed. Most promising structural concepts and materials from Paper E and Paper F are combined into an envisaged tri-layer structural concept. A CZM based impact model is developed and validated with experiments for (a) an aluminium grillage and (b) carbon fibre sandwich structure. Further, a stochastic quasi-static ice pressure loading model is developed. Three tri-layer concept candidates – aluminium grillage, stiffened sandwich and metal-FRP composite are evaluated using the developed loading models. The three concepts are compared for mass, structural response and energy, emissions and costs using life cycle analysis (LCA).

1.5 Thesis Organization

The thesis is divided into six chapters.

Chapter 1: Introduction

The chapter introduces WPT’s growing interest as well as its primary challenges. The need for developing efficient commuter ferries and lightweight hulls for ice operations are expressed. The research objectives are laid in this context. Finally, the research methodology is described, and a summary of research contributions is expressed.

Chapter 2: Tailored Standard Commuter Craft

First, the background is established by describing the present state of WPT in the form of 7 key observations. Then, principal challenges of WPT are identified and categorised as regulatory and technical challenges. First, the regulatory challenges are explored. For this, a standard structure for operational requirements is proposed. Using the structure, a framework for modularization of ferries is presented in the form of a general methodology. Standard ferry dimensions and operational speed ranges are presented. With the standard form as a skeleton, a modular ferry platform is developed. The potential of tailoring the modular ferry according to operational scenarios is presented with the help of key examples.
Then, a methodology for assessing ferry performance with respect to the operational requirements is introduced using AHP. Two applications of the method are presented and a graphical user interface (GUI) example for the PTPs is expressed. (Paper A & B), (additional reading: Paper N2, N3, N4, N7 [10-13]).

Chapter 3: Freshwater ice operations

This chapter introduces the technical challenges associated with ice operations in the Nordic region. First, local ice properties in Lake Mälaren, Sweden are outlined, and the challenges associated with missing data is expressed. Then the nature of ice hull interaction including different mechanisms in different types of ice is explored. Next, the techniques for estimating ice loads on hulls in the absence of experimental data is investigated. These include probabilistic methods, analytical methods and rule-based design. Finally, an uncertainty analysis is performed considering all factors that influence the operational time window in freshwater ice operations. (Paper C & D), (additional reading: Paper N5, N6 [5, 14]).

Chapter 4: Quest for a lightweight hull

This chapter outlines the investigation of different structural concepts subjected to different phases of ice-hull interaction. First the state of the art in ice classed vessels is explored to lay the neutral ground for comparison. In this regard, an inland waterway barge is analysed for increasing levels of quasi-static ice pressure using non-linear finite element analysis. Next, the same barge designed with ice class rules is subjected to increasing levels of ice pressure and analysed. Next, other lightweight structural concepts and materials that are not yet found in practice are explored. The exploration is done for two types of loads – (a) quasi-static ice pressure and (b) impact loads. The significant parameters for the structural concepts along with parametric trends are identified. Finally, an LCA is performed for all structural concepts and materials. (Paper E & F), (additional reading: Paper N1 [15]).

Chapter 5: A lightweight ice-going hull concept

This chapter introduces a lightweight structural concept called the tri-layer structure based on the different stages of ice-hull interaction. Then, a realistic quasi-static loading model is presented considering the stochasticity involved in ice-hull interaction loads. Thereafter, a CZM impact model for ice is presented and validated with experiments for an aluminium grillage and carbon fibre sandwich. Next, three candidates for the tri-layer concept are presented and compared for the two loading mechanisms. (Paper F & G).

Chapter 6: Conclusions and Future work

This chapter summarises the broad conclusions derived from the thesis. With these conclusions as basis, opportunities for future work are identified.
There has been a resurgence in interest towards Waterborne public transportation (WPT) over the past decade due to contemporary transport challenges like need for better routing, urban congestion, and pollution. Several new WPT systems in cities like Copenhagen, New York, London have emerged [16-18]. Technological advancements such as autonomous navigation, modular design and electric propulsion systems are being explored. However, the adoption of WPT is not as straightforward as other transportation modes. To better understand WPT and its perceived challenges from the PTP’s standpoint, we performed a few background studies [10-12], which are presented in the next section.

2.1 Present state of WPT

Seven key observations were made with regards to WPT today [10]. They highlight both challenges and opportunities to improve the perception of WPT.

1. WPT consists of three distinct route types. These are summarised in Table 1. A direct relationship between the route type, corresponding ferry’s design and travel behaviour was observed. Route type A describes routes in the inner city arranged along a water body. The corresponding ferries have high speed hulls with general arrangement (GA) tailored towards a mix of comfort and mobility. Route type B connects stops across a water body. The corresponding ferries operate to-and-fro. They have double ender hulls with GA’s tailored towards large volume and dual entrances at ends. Route type C connects suburban areas to inner city. The corresponding ferries need energy efficient hulls, and their general arrangement (GA) is tailored towards comfort.

<table>
<thead>
<tr>
<th>Route type</th>
<th>Description</th>
<th>No. of stops</th>
<th>Total distance (NM)</th>
<th>Ferry Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: City</td>
<td>Service along a water body within the city</td>
<td>&gt;3</td>
<td>2 – 8</td>
<td>Bus comparable speed, High frequency, Accessible, Multimodal integration</td>
</tr>
<tr>
<td>B: Bridge</td>
<td>Service across water bodies, similar in function to bridges</td>
<td>2 – 3</td>
<td>&lt;2</td>
<td>High frequency, Short turnaround, Quick embarkation, Large capacity</td>
</tr>
<tr>
<td>C: Suburban</td>
<td>Service connecting suburban regions to city</td>
<td>&gt;2</td>
<td>8 – 12</td>
<td>Comfort, Weather independent operations, Reliability</td>
</tr>
</tbody>
</table>
2. Ferry scheduling needs to be well balanced between keeping it attractive for commuters and adjusting towards economical constraints. Further, scheduling needs to be facilitated towards a multi-modal possibility. Scheduling showed a strong dependence towards route type, route length, commuter volume, number of vessels and capacity.

3. WPT’s success is closely associated with its ability to integrate with other modes of transportation [19]. Transit network integration pitches WPT as a reliable and regular mode of transport and arouses confidence among commuters.

4. Terminal location, design and infrastructure play a big part in WPT’s perception. Its success lies in terminals that are situated at key locations and are accessible to everyone, including those with special needs. In addition, they should be integrated with other transport modes in the form of hubs. The hubs should provide shelter as well as routing information.

5. Commuters associate WPT with qualitative metrics like comfort and calmness. These are perceived to be more important than quantitative metrics like travel time [12]. Tailoring towards passenger perception through services like Wi-Fi (e.g., Rotterdam), onboard food /drinks (e.g., London) play a large part in boosting perception.

6. There is a large diversity in ferry designs and a large mismatch between the operational requirements and the ferry’s characteristics. The hulls varied from monohulls to catamarans. The capacities ranged from 80 passengers in Copenhagen to 2100 in Istanbul. The speeds varied from 10 knots in Stockholm to over 35 knots in San Francisco. The hull materials varied from steel to fibre-reinforced plastics (FRP). The propulsion systems varied from fossil fuels to electric drives to hybrids. A corresponding observation was that many operational ferries were second-hand refurbished vessels, showing a low operational efficiency.

7. Ferries generally have a large operational cost and environmental impact. Largest contributors towards this were poorly designed hulls, inefficient power-systems, and mismatched ferries on corresponding route types. Further, the requirement for additional service personnel on board increases the operational costs.

2.2 Principal challenges

Based on the key observations, WPT’s challenges can be divided into regulatory and technical challenges. The regulatory challenges are funding constraints, competition from other modes, lack of political will and lack of legislation [20]. Political and institutional arrangements can influence WPT tremendously due to conflicting agendas between authorities as can be observed in Bangkok’s impeded efforts towards fleet modernization and route expansion. In Sweden, land use policy represents the biggest challenge towards having a uniform network that crosses policy boundaries [11].

PTPs find it difficult to procure ferries ‘off-the-shelf’ or have them ‘made-to-order’ in a relatively quick and cost-efficient manner. An added impediment is a lack of a uniform understanding of operational requirements, causing hesitancy in communicating them [4]. These factors contribute to the reluctance in the minds of PTPs, adding to their view of WPT being cumbersome to implement. They find opting for alternate modes easier.
Among technical challenges, the fourth and the sixth key observations: terminal and ferry design, represent the core. With respect to ferry design, the first challenge is to have a uniform framework that can tailor the ferry corresponding to stakeholder preferences, in a cost and time efficient manner. This would lead to high operational and environmental efficiency [10], comparable with alternate modes. In Sweden, weather dependent operations is identified as the biggest technical challenge [11] that affect passenger perception due to decreased reliability of services in winter ice. The challenge is to have a fuel-efficient lightweight ferry that is strong enough to sustain ice loads. Other technical challenges include emission free propulsion, autonomous navigation and supporting infrastructure.

The challenge with terminal design revolves around ideal placement. It must balance between facilitating effective transportation with inter-modal connectivity and avoiding urban regimes for gentrification [11]. Further, they need to reflect passenger expectations (5th key observation).

If ferry and terminal design can be made robust and attractive, they can mitigate several of the regulatory challenges and cause a shift in PTPs perception [3].

2.3 Operational requirements

As noted earlier, there is a lack of standardized operational requirements describing WPT. PTPs are left to define their own versions of requirements which may or may not include all stakeholder expectations. Moreover, such requirements may be subjective (e.g., metrics like calmness, ambience), leading to ambiguousness in interpretations. Correspondingly, we propose an operational requirement’s structure that has standard definitions, leading to uniform and precise communication (See Figure 3). The operational requirement’s structure can guide ferry design and alleviate some of the earlier identified challenges.

The operational requirement’s structure is built upon the three pillars of sustainable development. It incorporates stakeholders from economic, social and environmental sectors while including material, technological, economic, legal, environmental and human-related considerations that change with time [21]. Further care is taken to incorporate differences arising from regional, cultural, population density, geographical and regulatory diversity [22].

The operational requirement’s structure goes from broad to detailed design arranged in 3 levels (See Figure 3). The primary level corresponds to the route type (See Table 1).
The secondary level is synonymous with mission requirements of design spiral method [23]. Among its three sublevels, local climate conditions refer to all weather-related factors that the PTP must communicate with the vessel manufacturer/seller. E.g., wave, current, ice data. Next, the operator requirements correspond to PTPs assessment of local stakeholder needs. E.g., the operator might specifically request for a bridge deck. Finally, the regulatory body requirements include all regulations issued by classification societies, governmental agencies, and legislative authorities. E.g., local bridge clearance, IMO seakeeping check.

The tertiary level’s purpose is to optimise the ferry to maximise economic, social and environmental performance. These are driven by the sacred expectations laid down in Stenius, Garne [24], corresponding to the three pillars of sustainability. The four metrics under economic performance reflect life cycle repercussions for the PTP. The metrics under social performance reflect passenger perception, gathered from surveys [12]. Finally, environmental performance metrics reflect environmental impact through emissions and marine noise.

Definitions of metrics can be found in Paper B[4] for further reading. Using the requirements’ structure, we can define what a WPT ferry might look like.
2.4 Framework for modularization

Based on the operational requirements structure, a multitude of permutations and combinations of ferry designs are possible. Going by the present ship design methods like design spiral [23], ship synthesis [25] and system-based ship design [26], the design and production of ferries can be a long and thorough task. By shifting to a platform architecture, one may essentially produce a large variety of WPT vessels with comparably low levels of complexity [27]. Modular design is an established platform architecture strategy. We use it to divide the ferry into functionally-independent modules that can be individually tailored. By doing so, we can potentially flatten the ship design spiral.

The methodology in creating a ferry product family is described in Figure 4.

Figure 4: Methodology for creating a ferry product family. The methodology may be adapted to create other vessel families.

The first step is the identification of vessel capacities based on capacity constraint equations. If the deduced capacities fall within contemporary trends and meet local requirements, we solve for principal dimensions (L, B, D, H). These dimensions and ratios must fulfil basic stability, seakeeping and resistance checks, local constraints, and contemporary trends. Next, hulls are developed based on these principal dimensions. They undergo design improvements while balancing resistance, seakeeping, and stability. The vessel’s overall dimensions and hull-form defines the skeleton of the vessel. In our case, two variants were identified to represent WPT. Their principal dimensions are summarised in Table 2.
Table 2: Two standard ferry sizes for inland WPT and their principal parameters.

<table>
<thead>
<tr>
<th>Ferry Characteristic</th>
<th>Small variant</th>
<th>Large variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route type</td>
<td>City/ Bridge/ Suburban</td>
<td>City/ Bridge/ Suburban</td>
</tr>
<tr>
<td>Design speed (kts)</td>
<td>8 – 14</td>
<td>8 – 14</td>
</tr>
<tr>
<td>Froude number</td>
<td>0.42 – 0.53</td>
<td>0.37 – 0.46</td>
</tr>
<tr>
<td>Energy (kWh/km/pax)</td>
<td>0.01 – 0.45</td>
<td>0.005 – 0.4</td>
</tr>
<tr>
<td>Capacity (pax)</td>
<td>100 – 350</td>
<td>200 – 450</td>
</tr>
<tr>
<td>Deck area (m²)</td>
<td>138 m²</td>
<td>180 m²</td>
</tr>
<tr>
<td>Dimensions (m)</td>
<td>L = 22</td>
<td>L = 28.6</td>
</tr>
<tr>
<td></td>
<td>B = 6.4</td>
<td>B = 6.4</td>
</tr>
<tr>
<td></td>
<td>T = 1.2 – 1.7</td>
<td>T = 1.2 – 1.7</td>
</tr>
<tr>
<td>L/B</td>
<td>3.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Displacement (t)</td>
<td>44 – 95</td>
<td>61 – 117</td>
</tr>
</tbody>
</table>

Next, we move to platform architectural phase of the design methodology. To identify functionally-independent modules, we use function structure heuristics (FSH) [28]. FSH is recommended considering its suitability towards product families. The process is achieved by visualising flows as shown in Figure 5. For the ferry, five groups and corresponding sub-groups are identified as shown in Figure 6.

Figure 5: Function structure of a commuter ferry developed using FSH for identifying modules and sub-modules. Colours identify different function flows.

The dimensions of the modules are calculated by solving GA constraints relating utility and component dimensions, clearances, accessways and road transport size limitations. Next, interfaces are designed such that they are accessible, standardized and connected kinematically [29]. We call the vessel’s design till this stage as its ‘skeletal form’. This form represents a template.
In the final phase, the module templates are independently tailored to meet operational requirements, resulting in an efficient ferry. Next, we look at the modular ferry platform.

### 2.5 The modular ferry platform

The platform represents a series of ferries that have the same broad dimensions but fulfil diverse operational roles due to their inherent customizability.

#### 2.5.1 The ferry template

In the previous section, we identified five module groups and corresponding sub-modules (see Figure 5). The modular hierarchy is shown in Figure 6.

The first module group Superstructure captures the flow of passengers and crew. It has four types of functionally-independent sub-modules (See Figure 7). Sub-module type X encloses amenities, entrances, and navigation sub-functions. It also integrates wiring, sewage and exhaust piping and HVAC with the hull. Its arrangement differs in the forward and aft. They are illustrated in Figure 8.
Sub-module type Y is designated to hold bicycles, luggage and standing passengers. Sub-module type Z adopts seating and standing spaces. On grounds of commonality, their sub-functions can be interchanged. Sub-module type E are located at both ends of the superstructure. They serve as exits as well as provide structural strength. They are envisaged in 3 standard sizes corresponding the route and hull type.

The remaining three module groups are Control systems, Engine and Transmission and Propulsion. Most components under these groups are already obtained from manufacturers as modules. However, they lack a common interface and it varies between companies [27]. To preserve commonality [21], we measured standard dimensions of different components and proposed upper size limits in Cheemkurthy and Garme [3]. This may pave the path towards developing standardized kinematically integrated interfaces, resulting in a plug-and-play style of setup.

The hull module group can be chosen from a set of standardized hulls. Four such hulls are investigated in Paper A [3]. Standardization is possible because (a) WPT generally operates in sheltered waters with mild climatic conditions and (b) we have deduced standard overall vessel dimensions in the skeletal form.

### 2.5.2 Tailoring by modularization

The advantage of modularization is that functionally-independent modules can be individually tailored towards operational requirements. Potentially, each sub-module can have 100s of variants leading to abundant tailoring possibilities. E.g., Figure 9 shows four different designs for the sub-module type Z, that are suitable in different conditions.
Figure 9: Four functional variants of sub-module type Z are shown to the right. The third variant’s 3D representation in a modular ferry is highlighted. The four variants represent a workstation for route type C, seating for route type A, an open layout for route type B and transformable conference space to be used during downtimes.

The vessel may be tailored by mapping modular definitions to operational requirements (see Figure 10). Here, three examples of tailoring the modular ferry are demonstrated.

Figure 10: Mapping diagram between modules and operational requirements. For each sub-module, relevant metrics are linked, which can drive tailoring.

2.5.3 Application examples

Route type A: City ferry
A city ferry in Brisbane is taken as basis to adapt the modular ferry. This is done by choosing appropriate variants for each sub-module type. The submodules type Y and Z have been chosen such that the ferry has seats on either ends to cater for long distance commuters. The second submodule type Z’s layout is chosen to enable high commuter flow between stops 2-4 with quick access to side entrances on submodule type X.
Route type B: Bridge ferry
Here a bridge ferry (Route type B) from Amsterdam is taken as basis to tailor the modular double ender ferry. The submodule types Y and Z focus on bicycle and standing passenger capacity with one row of folding seats along the edges. The bikes are arranged to ensure smooth embarkation and disembarkation. Submodule type X have wheelchair spaces close to the entrances. The double ended ferry has wide exit ramps on both ends that can extend out.

Figure 11: (a) Comparison of Brisbane ferry and Modular City ferry (highlighted in red). (b) Brisbane ferry (photograph: Wikimedia commons). (c, e) Proposed modular city ferry. (d) GA of the city ferry for Brisbane.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Brisbane ferry</th>
<th>City ferry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>25 m</td>
<td>28.6 m</td>
</tr>
<tr>
<td>Beam</td>
<td>7.6 m</td>
<td>6.4 m</td>
</tr>
<tr>
<td>Capacity</td>
<td>260</td>
<td>310</td>
</tr>
<tr>
<td>Operational speed</td>
<td>15 kts</td>
<td>15 kts</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>Inland waterways</td>
<td>Inland waterways</td>
</tr>
</tbody>
</table>

Figure 12: (a) Comparison of Amsterdam ferry and Modular Bridge ferry (highlighted in red). (b) Amsterdam ferry. (c, e) Proposed modular bridge ferry. (d) GA of the bridge ferry for Amsterdam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Amsterdam ferry</th>
<th>Bridge Ferry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>33 m</td>
<td>28.6 m</td>
</tr>
<tr>
<td>Beam</td>
<td>9 m</td>
<td>6.4 m</td>
</tr>
<tr>
<td>Capacity</td>
<td>410</td>
<td>350</td>
</tr>
<tr>
<td>Operational speed</td>
<td>10.2 kts</td>
<td>10.1 kts</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>Inland waterways</td>
<td>Inland waterways</td>
</tr>
</tbody>
</table>
**Route type C: Suburban ferry**

Here a suburban ferry (Route type C) from Stockholm is taken as basis to tailor the modular ferry. Both submodule type Zs are configured for spacious and comfortable seating that promotes socializing. The forward submodule type X has a cafeteria with vending machines. The wheelchair spaces are placed close to the side entrances. The two submodule type Y’s stow bikes. The forward Type E submodule has a wide entrance for bike passengers. At the aft of the vessel, there is a WC, safety boxes and a luggage storage area in the aft submodule type X.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stockholm ferry</th>
<th>Suburban Ferry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>28 m</td>
<td>28.6 m</td>
</tr>
<tr>
<td>Beam</td>
<td>5.8 m</td>
<td>6.4 m</td>
</tr>
<tr>
<td>Capacity</td>
<td>190</td>
<td>223</td>
</tr>
<tr>
<td>Operational speed</td>
<td>10 kts</td>
<td>10.1 kts</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>Winter ice</td>
<td>Winter ice</td>
</tr>
</tbody>
</table>

**Figure 13:** (a) Comparison of Stockholm ferry and Modular Suburban ferry (highlighted in red). (b) Stockholm ferry (photo: Harsha Cheemakurthy). (c, e) Proposed modular suburban ferry. (d) GA of the suburban ferry for Stockholm.

Modularization presents tremendous potential towards tailoring the ferry towards operational requirements. However, choosing among 1000s of alternatives can be a daunting task. Further, there is no way to measure if the chosen ensemble of modules is efficient or not. Correspondingly, we developed a method to evaluate ferries with respect to the operational requirements in an objective manner. Alternate uses of the method are (a) performance assessment of ferries, (b) identification of strengths and weaknesses for targeted refurbishment, and (c) design aid at shipyards.

### 2.6 Assessment of ferries with respect to operational requirements

The evaluation falls under a classic multicriteria decision making (MCDM) problem. Several approaches have been discussed in literature [30-34]. Among these, we choose the analytical hierarchic process (AHP) for its simplicity and wide industrial applications. AHP uses utility functions to aggregate multiple criteria into a single dimensionless index. For the ferry, we call this index as the design performance index (DPI). It benchmarks competing designs against evaluation criteria and ensures objectivity in decision making.
2.6.1 Methodology

The performance is evaluated based on the tertiary level of the operational requirements structure from Figure 3. In total, there are 12 sub-criteria arranged under 3 criteria: economic (E), social (S) and environmental (V). Their respective definitions are compiled in Table 3. The ferry is evaluated against these criteria. The resulting DPI is calculated as the product of evaluation sub-criteria weights \((Z_i)\) and performance ratings \((y_i)\) of competing designs as,

\[
DPI_j = \sum_{i=1}^{12} Z_i \times y_i^{M=E/S/V}\j
\]

**Table 3**: Performance evaluation criteria at tertiary level of the operational requirements.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Criterion (Sub-criterion)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C^E)</td>
<td>Economic Performance</td>
<td></td>
</tr>
<tr>
<td>(C^E_1)</td>
<td>Manufacture Cost</td>
<td>Manufacturing cost of the vessel</td>
</tr>
<tr>
<td>(C^E_2)</td>
<td>Operational Cost</td>
<td>All operating costs including wages, supplies, fees, and amenities</td>
</tr>
<tr>
<td>(C^E_3)</td>
<td>Maintenance Cost</td>
<td>Costs include part replacement, repairs, and service.</td>
</tr>
<tr>
<td>(C^E_4)</td>
<td>Recycling/Other Cost</td>
<td>All other costs including recycling, insurance and so on.</td>
</tr>
<tr>
<td>(C^S)</td>
<td>Social Performance</td>
<td></td>
</tr>
<tr>
<td>(C^S_5)</td>
<td>Ambience</td>
<td>Ability to view and access outdoors, indoor ambience, onboard noise, productivity</td>
</tr>
<tr>
<td>(C^S_6)</td>
<td>Comfort</td>
<td>Amenities including seating, open spaces, toilets, food and drink, embarkation ease and ship motions for comfortable travel</td>
</tr>
<tr>
<td>(C^S_7)</td>
<td>Service</td>
<td>Travel time and speed; Accessibility for passengers with bikes, trolleys, wheelchairs; Year-round operability; Reliability</td>
</tr>
<tr>
<td>(C^S_8)</td>
<td>Safety</td>
<td>Fire safety, safety against capsizing and damage, evacuation measures</td>
</tr>
<tr>
<td>(C^V)</td>
<td>Environmental Performance</td>
<td></td>
</tr>
<tr>
<td>(C^V_9)</td>
<td>Recycling</td>
<td>Environmentally detrimental emissions in recycling phase</td>
</tr>
<tr>
<td>(C^V_{10})</td>
<td>Manufacturing</td>
<td>Environmentally detrimental emissions in manufacturing phase</td>
</tr>
<tr>
<td>(C^V_{11})</td>
<td>Operational</td>
<td>Environmentally detrimental emissions in operational phase</td>
</tr>
<tr>
<td>(C^V_{12})</td>
<td>Noise</td>
<td>Levels of noise pollution</td>
</tr>
</tbody>
</table>

The process of evaluating weights and performance ratings, leading to DPI is outlined in Figure 14. First, ‘degree of relative importance’ is chosen by the user following Table 4 as a guide in pair-wise comparisons. The relative importance values are used to evaluate crisp weights. However, assigning crisp-scale values (see Table 4) can be a source of reluctance and uncertainty, as the user might be unsure [35]. This challenge can be addressed by choosing a fuzzy approach where relative importance represents a range of values (see fuzzy scale in Table 4). After comparing several fuzzy approaches, we found the fuzzy optimization approach [36] yielded the most reliable results.
Figure 14: Methodology for evaluating the DPI of an alternative using AHP.

Table 4: Criteria for assessing degree of relative importance of criteria using crisp and fuzzy scales.

<table>
<thead>
<tr>
<th>Linguistic scale for importance</th>
<th>Crisp scale [34]</th>
<th>Crisp reciprocal scale</th>
<th>Fuzzy scale [37]</th>
<th>Fuzzy reciprocal scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just equal</td>
<td>1</td>
<td>1</td>
<td>(1, 1, 1)</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>Equally important</td>
<td>1</td>
<td>1</td>
<td>(1/2, 1, 3/2)</td>
<td>(2/3, 1, 2)</td>
</tr>
<tr>
<td>Weakly more important</td>
<td>3</td>
<td>1/3</td>
<td>(1, 3/2, 2)</td>
<td>(1/2, 2/3, 1)</td>
</tr>
<tr>
<td>Strongly more important</td>
<td>5</td>
<td>1/5</td>
<td>(3/2, 2, 5/2)</td>
<td>(2/5, 1/2, 2/3)</td>
</tr>
<tr>
<td>Very strongly more important</td>
<td>7</td>
<td>1/7</td>
<td>(2, 5/2, 3)</td>
<td>(1/3, 2/5, 1/2)</td>
</tr>
<tr>
<td>Absolutely more important</td>
<td>9</td>
<td>1/9</td>
<td>(5/2, 3, 7/2)</td>
<td>(2/7, 1/3, 2/5)</td>
</tr>
</tbody>
</table>

Next, cumulative sub-criteria weights are evaluated as the product of its weight ($W_m^i$) and its overlying criteria weight ($w_t^m$) as,

$$Z_i = W_m^i \cdot w_t^m$$

(2)

The cumulative weights undergo a consistency check to measure the quality of weight selection. If unsuccessful, the user must pick new relative importance values.

Next, we evaluate the modules/ferry against the 12 evaluation criteria. We call them performance ratings. To preserve objectivity, all evaluations must be quantitative. This is possible for economic and environmental criteria which can be measured in terms of currency and emission quantities. But social performance evaluation is subjective, and one must rely on passenger surveys to gauge them. Since this can be tedious, general guidelines for objectively evaluating social performance are proposed in Paper B [4].
Based on the evaluated sub-criteria weights and performance ratings, DPI for the ferry is evaluated using Eq. (1). Criteria wise DPIs are calculated as,

\[ Y_{j,ECONOMIC}^n = \sum_{i=1}^{4} w_i^E \times y_{i}^{M=Ej} \]  
(3)

\[ Y_{j,SOCIAL}^n = \sum_{i=5}^{8} w_i^S \times y_{i}^{M=Sj} \]  
(4)

\[ Y_{j,ENVIRONMENT}^n = \sum_{i=9}^{12} w_i^V \times y_{i}^{M=Vj} \]  
(5)

Thus, one knows how the ferry performs with respect to economic, social and environmental criteria. Further, it is possible to see the performance against underlying sub-criteria. This helps identify the candidate’s strengths and weaknesses.

Here, two applications of the method are demonstrated – (a) assembly of a modular ferry, and (b) comparative evaluation of ferries in Stockholm.

### 2.6.2 Application: Assembly of a modular ferry

We can use the proposed method to choose the best configuration for the given operational conditions. Our goal is to maximize economic, social, and environmental performance. In the case of a modular ferry, we calculate DPIs of sub-modules first. The mean DPI of the submodules is the DPI of its overlying module. Similarly, the DPI of the modular ferry is the mean of its constituent module DPIs.

For this illustration, assume there are 3 module groups: superstructure, hull, and engine (see Figure 15). The superstructure module is an assembly of 2 x 4 sub-module types as shown in Figure 7. Each sub-module and module have 4 competing variants (descriptions in Table 5).

Figure 15: Superstructure sub-modules that are considered in the application example.
Table 5: Hypothetical description of module/sub-module alternatives.

<table>
<thead>
<tr>
<th>Module</th>
<th>Sub-module</th>
<th>Alternative</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X1</td>
<td>Hull access, safety equipment outlet, storage, recyclable, side entrances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X2</td>
<td>Hull access, storage and safety outlet, sound proof material, side entrances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X3</td>
<td>Driver cabin, cold food cafeteria, special access place, WC, side entrances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X4</td>
<td>Driver cabin, hot food cafeteria, special access place, WC, side entrances</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Y1</td>
<td>Mechanized bike stowing with comfortable seating for bikers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y2</td>
<td>Bike stowing spaces, seating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y3</td>
<td>Bike stowing spaces</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y4</td>
<td>Space of standing passengers, wide open space, noise absorbing furnishings</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Z1</td>
<td>Combination of seating and standing space, high passenger capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z2</td>
<td>Combination of seating and standing space, premium quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z3</td>
<td>Seating intensive, large inter-seat space, premium quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z4</td>
<td>Seating intensive, economical, high passenger capacity</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>N1</td>
<td>Sealed entrance with large windowpanes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>Front opening entrance without windows</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3</td>
<td>Front opening entrance modules with large windowpanes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H1</td>
<td>Monohull, FRP – steel hybrid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>Monohull, Aluminium – steel hybrid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>Monohull, FRP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>Monohull, Steel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G1</td>
<td>Electric engine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G2</td>
<td>Conventional diesel engine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G3</td>
<td>Diesel engine noise free</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G4</td>
<td>Diesel – electric hybrid engine</td>
<td></td>
</tr>
</tbody>
</table>

The evaluation of sub-modules for hypothetical weights and performance ratings are summarized in Figure 16. The black circles indicate the best performers.

![Figure 16: Overall DPI for all alternatives. The candidates are colour-coded for submodule/module types. Best alternatives are denoted with circles. Performance with respect to economic, social, and environmental performance can be found in Paper B [4].](image)

If we assemble the ferry with these chosen modules, we obtain the most suitable ferry configuration for the given operational conditions. A DPI<1 indicates scope for improvement. By identifying strengths and weaknesses of weak modules, targeted design
improvements may be made to increase the operational efficiency of the modular ferry. An example of how the graphical user interface for tailoring might look like, is shown in Figure 17.

![Figure 17](image.png)

**Figure 17:** An example of a GUI for assembly of a modular. Respective DPIs are output on the lower right corner.

### 2.6.3 Application: Evaluation of ferries

We use the method to evaluate three existing ferries on line 80 in Stockholm and compare them in Figure 18(a). Ferry-1 is an electric ferry with an aluminium hull. Ferry-2 is an old diesel-powered vessel constructed with steel. Ferry-3 is a new diesel-powered ferry with scrubbers and a composite hull. Hypothetical criteria weights were chosen for the illustration and approximate ferry data was sourced from operators.

![Figure 18](image.png)

**Figure 18:** (a) Performance comparison of three ferries operating on Line 80 in Stockholm. (b) Break-down of social criteria.

We can objectively see that Ferry-1 is the best performer with a DPI of 0.71 while Ferry-2 is the worst performer with DPI of 0.4. We also see relative strengths and weaknesses. For example, if we further investigate social performance in Figure 18(b), service and comfort are weak performers while ambience and safety are strengths. This paves the path towards targeted refurbishment.
2.7 Concluding remarks

In this chapter we identified a series of regulatory and technical challenges that create reluctance in the minds of PTPs when they think of adopting WPT. Their difficulty in procuring efficient ferries in a quick and cost-efficient manner is addressed through the proposal of a ferry product family using platform architecture. Modular design is proposed, and the methodology of creating a family of ferries is described. Through the process, we proposed two standard sizes for WPT ferries and showed that they can be as efficient as buses in terms of emissions and mobility. In addition, we address the problem of an operational-role mismatch between ferries and operational requirements. We propose a standard structure for operational requirements and a method to evaluate ferries against them. Such a method will make decision making objective for PTPs during ferry procurement, refurbishments and assembling modular ferries. In the following chapters, we focus on addressing the technical challenges that WPT ferries face during operations in ice.
Chapter 3
Freshwater Ice Operations

Several technical challenges were identified in Chapter 2. Among these, operation in ice is foremost in cities like Stockholm where both ice and non-ice conditions can be found during the year. Disruptions in WPT due to ice reduces reliability of the service which affects social perception. Correspondingly, vessels are ice strengthened using larger steel scantlings. A drawback is that larger displacements result in higher emissions and reduces payload capacity. Design optimizations and alternate lightweight structural concepts may be explored if local ice loads are known. This chapter looks at understanding ice-hull interaction and related forces in freshwater ice.

3.1 Ice and its properties

In nature, ice is found in over 18 types of packing geometries that can be crystalline and amorphous. The presence of impurities, dissolved substances and air make this geophysical material extremely complex to quantify in terms of physical laws. The stochasticity in ice properties translates to the unpredictability associated with quantifying ice-hull interaction forces. The forces are further influenced by hull geometry and relative velocity [38]. As such, there is a lack of reliable ice models today [39]. But, focusing on a particular type of ice helps in reducing the stochasticity involved.

We focus on the freshwater ice found in Lake Mälaren, Sweden. The ice is classified as light first year ice [40]. The ice properties can be divided into (a) physical characteristics, and (b) mechanical properties. The physical characteristics are sourced from the Swedish Meteorological and Hydrological Institute (SMHI) while the mechanical properties are sourced from previous studies [40-43].

3.1.1 Physical Characteristics

From Figure 19(b), during winter months, the ice thickness is < 30 cm for about ~89% of the time. The yearly mean is 16 cm and a peak of > 70 cm have been observed on rare occasions (1988, 1994, 1996 and 2003). From Figure 19(c), level ice is the most common type of ice, occurring 48% of the time. We also observe small to large ice floes occurring about 22% of the time. Lastly, we find brash ice towards the end of winter, occurring at about 17% of the time.
Each type of ice affects different parts of ship operations. E.g., level ice causes both impulse, dynamic and quasi-static pressure loads on the hull; Ice floes cause impact loads on the hull, and brash ice increases the ice resistance. Corresponding to this, appropriate design and navigation strategies must be adopted.

### 3.1.2 Mechanical Properties

Ice flexural strength is the most relevant factor for level ice-hull interaction since the predominant mode of ice breaking is by bending failure. In nature, one does not find uniform flexural strength in an ice field. This is due to local differences from dissolved impurities, forming conditions and extrinsic parameters like air temperature, humidity, salinity, pressure and porosity [40]. However, we assume uniformity and homogeneity for engineering applications [44]. Due to a lack of data for Lake Mälaren, we source flexural strength from other freshwater bodies like the Great lakes [41] and Lake Michigan [43]. The rest of the mechanical properties are calculated from literature [40, 45]. Table 6 summarises mechanical properties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>920</td>
<td>$\rho \text{[kg/m}^3\text{]}$</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$10^9$</td>
<td>$E \text{[Pa]}$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>$\nu$</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>167</td>
<td>$\sigma_t \text{[kPa]}$</td>
</tr>
<tr>
<td>Flexural strength*</td>
<td>648</td>
<td>$\sigma_f \text{[kPa]}$</td>
</tr>
<tr>
<td>Compressive strength**</td>
<td>up to 38</td>
<td>$\sigma_c \text{[MPa]}$</td>
</tr>
<tr>
<td>Crushing strength</td>
<td>196</td>
<td>$\sigma_{pc} \text{[kPa]}$</td>
</tr>
</tbody>
</table>

* Flexural strength noted from Great Lakes [41].
** Noted during field tests [46].

Figure 19: Distribution of physical ice characteristics between 1983 – 2017 in Lake Mälaren. (a) Ice concentration. Fast ice with high concentration is predominant. (b) Ice thickness predominantly varies between 5 and 30 cm. (c) Ice type. Level ice is predominant.
Next, we look at ice-hull interaction mechanisms and lay the foundation for calculating ice loads.

### 3.2 Ice hull interaction

The interaction between ice and ship hulls can be of several types: direct and indirect impact collisions, advancement in level ice, ice fields with ridges, in brash ice and vessel’s jamming between two compressive ice fields [47]. We are most interested in advancement in level ice and impact collisions with floes since they are the most prevalent types of ice (see Figure 19 (c)).

#### 3.2.1 Ice failure mechanisms

If we look at advancement in level ice, the ice-hull interaction can be represented as the crush-break-displace process (see Figure 20). On initial impact, localized crushing between the ice plate’s free edge and vessel’s contact zone is observed. The vessel’s forward motion causes the vessel to climb over the ice, which increases the contact area causing more crushing and introduces flexural loads on the ice plate. The resulting flexural failure induces cracks in ice, resulting in brittle failure. Finally, the broken pieces are swept towards the aft due to hydrodynamic forces.

![Figure 20: Ship advancement in level ice: crush-break-displace interaction scenario.](image)

Ice usually fails as a combination of crushing, bending, and shearing. The likelihood of predominant failure mode depends on the hull shape, ice’s mechanical properties and relative speed. Ice crushing failure is dependent on the uni-axial compressive strength of ice [48]. Failure entirely due to crushing is rare and occurs about 1% of the time as observed in experimental studies by Bekker, Sabodash [49]. However, crushing contributes to one of the highest forces [50]. Failure due to bending causes very high local loads in the bow’s ice belt region. It is dependent on the flexural strength of ice. Failure due to shearing is more prevalent in the midship region on the vessel’s vertical sides [51] when there is shearing of ice between the ice plate and moving vessel.

With these failure mechanisms as basis, we are interested in estimating the magnitude of corresponding loads. But since most existing methods and experiments have been based on sea ice, load estimation in freshwater ice will be subject to uncertainties. While on one hand, a conservative approach leads to a safe vessel, on the other hand, it leads to a heavier vessel, lower payload capacity and higher economic and environmental impact.
3.3 Ice Loads

The loads on the vessel in ice can be split into structural loads and ice resistance loads. The latter is not investigated here since it does not affect hull strength as much as the former. Interested readers on ice resistance may refer to literature [52-56].

The structural loads on the vessel can be divided into (a) global loads, and (b) local loads. Global loads are calculated by averaging the forces experienced by the hull during ice interaction. They cause spalling, splitting and micro-fracturing of ice [57]. They govern the vessel’s overall strength requirements and engine capacity to counter ice resistance [58]. The local loads are a result of local crushing of ice on the hull. Since contact areas are small, the resulting pressures can be much higher than global pressures [59]. The local high pressures are idealised into small rectangular contact areas called local design areas [58]. Within these, large impulse forces may occur in smaller critical areas called high-pressure zones (HPZ) [60]. These must be given special attention during the hull’s structural design. Figure 21 illustrates local design areas.

![Figure 21: Illustration of local pressures and HPZ on the ship hull [61].](image)

3.3.1 Ice load estimation techniques

Several approaches to estimate ice loads can be found in practice. One is the engagement of ice experts who have their own ice load calculation methods but lack of transparency and discrepancies in estimations poses a question on their reliability [62]. Another technique is the use of discrete element method (DEM) and finite element method (FEM) coupled with damage models. Despite considerable research in this field, no approach has been found to be sufficiently validated to be used with confidence [63] because of the underlying complexities of capturing ice mechanics [64]. The third option is to use model tests which are recommended by classification societies and agencies [65]. While they are regarded as state of the art [66], controversies exist particularly around the validity of scaling laws [66, 67]. The last approach is to rely on empirical and semi-empirical methods given by classification societies [61, 68, 69] which are most widely accepted as the current state of the art.
In our case, we lack freshwater ice’s empirical data which adds to the uncertainty that riddles ice load prediction today. Correspondingly, we address the problem using a probabilistic approach. Later, we compare the results with analytical calculations and rule-based design.

### 3.3.2 Probabilistic model

The probabilistic model corresponding to an ice going barge is developed. The barge is chosen since data on its ice encounter frequency in Lake Mälaren are known. The same approach would also be valid for a WPT ferry. The probabilistic model can be expressed as a negative exponential curve relating encountered ice pressure ($\alpha$ [MPa]) with the contact area ($a$ [m$^2$]) as,

$$\alpha = Ca^D$$  \hspace{1cm} (6)

where, C and D are factors dependent on the experimental dataset. They reflect differences in ice characteristics and mechanical properties. A large value of C generally denotes heavy ice conditions. Pressure-area curves representing datasets collected in the arctic region are shown in Figure 22. The smallest magnitude datasets represent light first year ice [70, 71]. Correspondingly, we choose these as the parent dataset to predict conditions in Lake Mälaren. It is of interest to observe that the pressure area curves in Figure 22 provide estimates for local loads but not for HPZ loads.

**Figure 22:** Plot of nominal pressure vs contact area. The data is compiled from different sea ice experiments. The upper limit is a design curve valid for contact areas larger than 0.6 m$^2$, [70].

For the model, the chosen datasets are from Polar Sea: North Bering Sea (1983)[70] and Bering Sea (1986)[71]. These are adopted since they both represent light first-year ice and were closest to WPT conditions. The probabilities of exceedance for the datasets are taken as $P_e = 0.5$ and $P_e = 10^{-2}$, which result in two design curves as shown in Figure 23. The bottom most curve (Design 2) corresponding with North Bering Sea (1983) was picked as
most representative of WPT conditions because Design 1’s dataset consisted largely of interactions with ice floes, which are less common in WPT conditions. With adjustments for the number of interaction events in Lake Mälaren, the design curve is expressed as,

\[ \alpha = 0.265a^{-0.57} \]  

(7)

The probabilistic method is largely dependent on the parent dataset. It would be valuable to validate the results with experiments. In its absence, we rely on analytical models and classification society rules. Next, an analytical model to capture ice-hull interaction is investigated.

**3.3.3 Analytical model**

The validity of the results predicted from the probabilistic method was tested by performing analytical calculations. First, the crushing force was investigated using energy conservation methods [72, 73]. For this, an infinitely large static ice sheet is assumed. Then, flexural forces are predicted using the method developed by Lubbad and Løsset [38]. For this, we assume an infinite ice plate supported on a winker foundation, subjected to a circular uniform distributed load \( q \) representing ice pressure (See Figure 24).
For an ice thickness of 0.3 m, the bending force varies between $100 - 200$ kN as a function of vessel speed between $1 - 5$ m/s. The crushing force was found independent of ice thickness and varied between $1 - 5$ kN between $1 - 5$ m/s. The force prediction by the probabilistic method for 0.32 m ice thickness varied between $130 - 550$ kN. The large scatter is attributed to the differences in parent datasets.

Next, we look at rule-based design prescribed by classification society rules [61, 69] and compare the design pressures.

### 3.3.4 Rule-based design

Existing classification society rules provide scantling/design recommendations for navigation in sea ice. They are semi-empirical and are based on numerous field tests and research studies [74-78]. The WPT ferry in question falls under ice class 1B by Finnish Swedish Ice class Rules (FSICR)'s [61] classification. This is equivalent to IACS Polar Class 6 [69]. Corresponding pressure estimates are shown in Table 7.

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSICR 1B</td>
<td>Nominal</td>
<td>HPZ 1.71</td>
</tr>
<tr>
<td>IACS PC 6</td>
<td>Nominal</td>
<td>HPZ 1.71</td>
</tr>
<tr>
<td>Probabilistic Method</td>
<td>Rahman [71]</td>
<td>1.354</td>
</tr>
<tr>
<td></td>
<td>Taylor [70]</td>
<td>5.744</td>
</tr>
<tr>
<td></td>
<td>Lake Mälaren [5]</td>
<td>2.622</td>
</tr>
</tbody>
</table>

From Table 7, we find pressures predicted by rule-based design are lesser than those predicted by the probabilistic method for Lake Mälaren. This could be representative of freshwater ice’s higher strength than sea ice [40].

Next, we look at quantifying the uncertainties associated with operations in freshwater ice.

### 3.4 Statistical estimation of uncertainty

The lack of experimental studies in freshwater ice in addition to lack of its mechanical properties in the Stockholm region are a source of uncertainty. By quantifying these, together with other factors involved in ice operations, the operational time window (OTW) for a ferry may be estimated. This is useful for planning and boosting reliability under social performance [4].

We use a statistics method called variation, mode and effect analysis (VMEA) [79] to identify contributors to overall uncertainty for a barge that is operating in Lake Mälaren. The overall transport system consists of 5 primary criteria: Structural loads, Ship resistance, Ship strength, Machinery and Operations. These and respective sub-criteria were considered in the investigation (See Figure 25). Corresponding data was sourced from operators, data collection agencies and literature.
From the analysis, ice load evaluation methods were found to be the largest source of uncertainty (See Figure 26). The confidence on the evaluation methods can be greatly increased by conducting field tests or developing freshwater ice interaction models. Until then, we rely on rule based design [61, 68, 69] for our calculations. The next largest source of uncertainty is ice resistance estimation methods. However, this is not as critical since an underpowered vessel may not lead to a catastrophe of the same scale as an under-strengthened vessel.

In the next chapter, we use the predicted ice loads to investigate the development of lightweight ice going hulls.
3.5 Concluding remarks

Winter navigation in ice affected regions poses a serious technical challenge that affects reliability of WPT operations. Further, contemporary ice going vessels are designed using conservative rule-based design which increases the vessel displacement leading to lower payload capacities and higher resistance. To investigate solutions towards this challenge, we need a reasonable estimate of ice loads in freshwater ice conditions. We observed two associated challenges towards it. (1) Lack of ice representative models that accurately capture ice-hull interaction, and (2) absence of experimental data in freshwater ice. These challenges are overcome using a probabilistic approach. The resulting force corresponded with the analytical model, but the estimated pressure was larger than rule-based design estimate. An uncertainty analysis showed that ice load methods are the biggest cause. Through improvements in analytical models or execution of experiments, accurate ice loads may be calculated. These could be used for driving weight optimal designs resulting in higher environmental and economic performance. Until then, we rely on rule-based design since it is the most widely accepted method.
Chapter 4  
Quest for a Lightweight Hull

In the previous chapter, we noted that one of WPT’s biggest technical challenges is operations in ice. Non-ice going ferries cease operations during winter months which increases travel times as passengers need to rely on longer land-based routes. This lowers commuter perception towards WPT. The ferries which are designed for ice navigation are heavier than non-ice counterparts. This leads to greater fuel consumption and emissions with a reduction in payload during the ice-free period (~9 months). An ideal solution would be to have an ice-strengthened ferry that is comparable in emissions and fuel consumption as a non-ice going ferry by using a lightweight hull structure.

To achieve this goal, we first need a clear picture on the local structural response to ice loads. But we saw earlier that evaluation methods for ice loads are the largest source of uncertainty [6]. This corresponds with the reason why classification societies opt for a conservative approach and recommend steel. Further, most experimental data has been based on steel vessels.

To assess the repercussions of uncertainties surrounding ice load evaluation methods, we numerically investigate the survivability of a barge designed with (a) inland navigation scantlings [80] and (b) FSICR’s ice-classed scantlings [61] at progressive levels of pressure. The investigation will answer the fundamental question – is it a good justification to use steel with larger scantlings? Following this, we look at alternate structures and materials for different types of ice loading.

4.1 A steel barge in ice

The steel barge called Amice operates in Lake Mälaren during the non-ice period (see dimensions in Table 8). The barge’s scantlings in accordance with Inland navigation rules DNVGL [80] and ice navigation FSICR [61] are compiled in Table 9. The scantling calculations for ice navigation are done assuming vessel ice class 1B, corresponding to the local ice conditions in Lake Mälaren. The load predictions match that with IACS Polar Class 6 [69] which includes a simplified plastic collapse mechanism [15] (see Table 7).
**Table 8:** Principal Dimension of an inland waterway Barge: Amice.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Overall</td>
<td>135 m</td>
</tr>
<tr>
<td>Beam</td>
<td>11.45 m</td>
</tr>
<tr>
<td>Depth</td>
<td>4.25 m</td>
</tr>
<tr>
<td>Max Speed</td>
<td>13.7 kts</td>
</tr>
<tr>
<td>Draught</td>
<td>3.4 m</td>
</tr>
<tr>
<td>Power</td>
<td>1588 kW</td>
</tr>
<tr>
<td>Tonnage</td>
<td>3938 t</td>
</tr>
<tr>
<td>Vessel Type</td>
<td>River Barge</td>
</tr>
</tbody>
</table>

**Table 9:** Structural Scantlings of the Barge and FSICR prescribed scantlings for class 1B.

<table>
<thead>
<tr>
<th>Member</th>
<th>Barge scantlings [80]</th>
<th>Member</th>
<th>FSICR Scantlings [61]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate thickness</td>
<td>10 mm</td>
<td>Plate thickness</td>
<td>19.52 mm</td>
</tr>
<tr>
<td>Transverse Frame</td>
<td>$Z = 34 \text{ cm}^3, A = 13 \text{ cm}^2$</td>
<td>Transverse Frame</td>
<td>$Z = 162.3 \text{ cm}^3, A = 9.4 \text{ cm}^2$</td>
</tr>
<tr>
<td>Web Frame</td>
<td>$Z = 179 \text{ cm}^3, A = 34 \text{ cm}^2$</td>
<td>Ice Stringer</td>
<td>$Z = 484.9 \text{ cm}^3, A = 33.5 \text{ cm}^2$</td>
</tr>
<tr>
<td>Stringer</td>
<td>$Z = 179 \text{ cm}^3, A = 34 \text{ cm}^2$</td>
<td>Non-Ice Stringer</td>
<td>$Z = 344.9 \text{ cm}^3, A = 23.8 \text{ cm}^2$</td>
</tr>
</tbody>
</table>

where, $Z$ is the section modulus and $A$ is the cross-section area.

A representative hull panel is extracted from the bow region of the barge. The plate is assumed to be flat. The corresponding grillages are shown in Figure 27. The plates are subjected to pressure loads shown in Figure 28. The loading areas are chosen conservatively where the nominal area corresponds to IACS PC 6 recommendation ($0.31 \text{ m}^2$) [69] and HPZ area corresponds to the probabilistic method recommendation ($0.096 \text{ m}^2$) [5].

![Figure 27: Structural arrangement](image)

The progressively defined pressure magnitudes are quasi-statically loaded and unloaded as indicated in Figure 28. The first peak corresponds to FSICR prescribed ice pressure. The steps are designed to capture non-linear behaviour and identify the beneficial effects of strain hardening and membrane stresses. The investigation is done using finite element
method (FEM) using ANSYS’s Mechanical APDL solver. The modelling details can be found in Cheemakurthy, Zhang [15].

**Figure 28:** Pressure Load Steps for (a) Barge scantlings; (b) FSICR prescribed scantlings.

The load deflection curves in Figure 29 corresponds to the barge designed with inland-waterways scantlings. We observe strain hardening after each pressure application and notice plastic behaviour with increasing permanent sets. Structural failure is observed at a nominal pressure of 15.5 MPa and an HPZ pressure of 27.5 MPa. The reserve strength is not enough to withstand extreme pressures observed during experiments, which can be as high as 38 MPa [46]. Nevertheless, considering light first year ice, chances of encountering such pressures are low.

**Figure 29:** Load-Deflection curve for the first Grillage: Barge scantlings

The load-deflection curve for the FSICR designed barge in Figure 30 shows a greater structural resilience with a limiting nominal pressure of 22 MPa and a HPZ pressure of 39.6 MPa, corresponding to a safety factor of 7 over the structure’s elastic limit. Membrane stresses contributed to 27% of total stress capacity.

**Figure 30:** Load Deflection curve for the second grillage: FSICR prescribed scantlings.
From the investigation, we note a considerable contribution from strain hardening and membrane stresses towards the capacity of steel grillages. Even though high-speed light craft (HLSC) regulations accept plastic deformations up to 3 times plate thickness [81], permanent sets affect the vessel’s resistance and affect the safety perception of commuters, lowering the social performance. In addition, strain hardened hulls run the risk of brittle cracking at low temperatures. In conclusion, the study points towards the possibility that FSICR based scantlings are overdesigned, also observed by Kubiczek, Andresen-Paulsen [82].

We noted in chapter 3 that advancement in level ice and impact collisions with floes are most relevant in our case. For level ice interaction in Figure 20, the force-time curve is expressed in Figure 31. The ice bending-crushing phase can be idealised as quasi-static [83, 84] while first contact, fracturing and spalling loads can be expressed as dynamic. Correspondingly, we can deduce that quasi-static loading and impact loading are the two predominant ice-hull interaction modes. In the next sections, we investigate lightweight structural concepts and materials for these two types of loading.

**Figure 31:** Force-time curve for hull interaction in level ice.

### 4.2 Lightweight concepts suitable for large quasi-static pressure

Within marine construction, metal grillages and sandwich structures are the most frequently found structural concepts. We also see stiffened composite structures in high performance crafts [85] and stiffened sandwich structures in naval warships like the Visby class corvette [86]. For our analysis, we choose three concepts – metal grillage, sandwich structure and stiffened sandwich structure, represented in Figure 32. We note that the metal grillage is the heaviest but occupies the least volume while the sandwich structure is the lightest but occupies the most volume.

![Diagram showing the volume comparison of different structures](image)

**Figure 32:** The 3 structural concepts under quasi-static investigation. $M_x$ = mass and $V_x$ = volume occupied, where $x =$ Sandwich (S), Stiffened sandwich (T) and metal grillage (M).
In practice, the shape of the stiffeners on the stiffened sandwich looks differently. The stiffeners shown here are chosen to have a common metric for comparison with the metal grillage. This concept design is inspired from work done by Goel, Matsagar [87] on different configurations of stiffened sandwich panels.

To create a good comparative environment for the 3 concepts, the applied ice loads must have an equal magnitude and loading area. Since FSICR guidelines define the loading magnitude as a function of vessel displacement [61], we assume an equal vessel displacement for the three concepts by adjusting the barge’s ballast.

First, we define a representative hull panel in the bow region of the barge shown in Figure 33. The quasi-static ice load magnitude is taken as per FSICR rules defined in Chapter 3. The nominal pressure patch is taken as per IACS rules and HPZ patch area is taken from the probabilistic method. This combination of areas describes the most conservative case. A region of interest is demarcated within the panel area to omit any abnormal stresses developed at boundaries to be included [88].

![Figure 33: A representative inland waterway barge in Lake Mälaren is used as basis to develop a reference hull plate.](image)

We use FEM to simulate structural behaviour. The comparative framework is based on (a) residual strength, (b) rule-based stiffness compliance and (c) minimization of mass. For FRP sandwich structures, the failure criteria is characterized by Hashin Criteria.

While implementing FEM is a very handy tool, the output is highly sensitive to the input parameters, meshing and the structural model. In this regard, we performed convergence studies and validated our model with previous experimental results in literature [74], [89].

There are three outcomes from the study that we are interested in.

- Overall comparison of the three concepts for (a) strength and (b) stiffness with respect to (i) mass and (ii) thickness.
- Significant parameters and parametric interactions.
- Parametric trends.
The answers to these questions will help us understand which structural concept is most suited for ice operations. It will help us recognize most sensitive parameters so that maximum gain in residual strength may be extracted. Finally, it will help identify parametric ranges for which structures are viable.

The three concepts are parametrized geometrically and by material as shown in Table 10. The parametrization is done based on structural design calculations and rule-based design.

Table 10: Parametrization of structural concepts. (A spacing of 0.67 m between stiffeners/stringers denotes that there is no stiffener/stringer present under the pressure patch.)

<table>
<thead>
<tr>
<th>Structural concept</th>
<th>Structural element</th>
<th>Variants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Grillage</td>
<td>Plate thickness</td>
<td>10, 15, 20 mm</td>
</tr>
<tr>
<td>(486 cases)</td>
<td>Stiffener spacing</td>
<td>0.25, 0.5, 0.67 m (0.67 m: no ice stiffener)</td>
</tr>
<tr>
<td></td>
<td>Stringer spacing</td>
<td>0.5, 0.67, 1 m (0.67 m: no ice stringer)</td>
</tr>
<tr>
<td></td>
<td>Stiffener elastic section modulus</td>
<td>18.4, 57.3, 94.8 cm³</td>
</tr>
<tr>
<td></td>
<td>Stringer elastic section modulus</td>
<td>150, 303, 443 cm³</td>
</tr>
<tr>
<td></td>
<td>Materials</td>
<td>Structural Steel, Aluminium alloy</td>
</tr>
<tr>
<td>Sandwich Structure</td>
<td>Face single ply thickness</td>
<td>0.2, 0.3, 0.4 mm</td>
</tr>
<tr>
<td>(405 cases)</td>
<td>Thin core thickness</td>
<td>75, 175, 275 mm</td>
</tr>
<tr>
<td></td>
<td>Thick Core thickness</td>
<td>300, 450, 600 mm</td>
</tr>
<tr>
<td></td>
<td>Face ply angles</td>
<td>[±45/−45]_s, [±90/0]_s, quasi-isotropic</td>
</tr>
<tr>
<td></td>
<td>Plate and stiffener</td>
<td>Carbon fibre 235, 395, UD &amp; woven, E-glass</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Low Density core PVC 60, Nomex Honeycomb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Density core PVC 200, PET 200/320</td>
</tr>
<tr>
<td>Stiffened Sandwich</td>
<td>Face single ply thickness</td>
<td>0.2, 0.3, 0.4 mm</td>
</tr>
<tr>
<td>Structure</td>
<td>Thick Core thickness</td>
<td>150, 275, 400 mm</td>
</tr>
<tr>
<td>(1215 cases)</td>
<td>Thin Core thickness</td>
<td>60, 100, 140 mm</td>
</tr>
<tr>
<td></td>
<td>Face ply angles</td>
<td>quasi-isotropic</td>
</tr>
<tr>
<td></td>
<td>Elastic Section modulus stiffener</td>
<td>18.4, 57.3, 94.8 cm³</td>
</tr>
<tr>
<td></td>
<td>Stiffener spacing</td>
<td>0.25, 0.5, 0.67 m (0.67 m: no ice stiffener)</td>
</tr>
<tr>
<td></td>
<td>Plate and stiffener</td>
<td>Carbon fibre 235, 395, UD &amp; woven, E-glass</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Low Density core PVC 60, Nomex Honeycomb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Density core PVC 200, PET 200/320</td>
</tr>
</tbody>
</table>

4.2.1 Overall comparison

Figure 34 shows the residual stress safety factors (SSF) against mass and thickness for the three concepts. With respect to mass, the sandwich structure has the highest strength to mass ratio and is on average ~10 times lighter than the metal grillage and 1.5 times lighter than the stiffened sandwich. But considering a thickness limit of 240 mm (representative of maximum girder web height for the barge [61]), the sandwich structure is ~2-6 times lighter than the metal grillage and ~1.1-1.3 times lighter than the stiffened sandwich.
We see that the strengths of sandwich structure and stiffened sandwich structure are comparable with the former having a slightly lesser mass. However, in terms of core thicknesses for the two concepts, the stiffened sandwich is about 30-50 mm thicker. In terms of gross tonnage, this represents a tremendous volume. This motivates us to go for the stiffened sandwich as the more ideal candidate.

If PTPs are inclined towards adopting metal grillages, the aluminium grillage represents a potential candidate that weights ~2 times the sandwich panel and ~1.5 times the stiffened sandwich panel. In terms of thickness, it offers a far superior gross tonnage than the sandwich concepts.

In the study, it was noted that strength is more critical than stiffness. A comparison of concepts with respect to stiffness can be found in Paper E [7].

![Figure 34: Comparison of SSF with respect to mass and panel thickness for all structural concepts.](image)

4.2.2 Significant parameters

The identification of significant parameters was performed using the analysis of variance (ANOVA) method. The condition to reject the null hypothesis is a 95% confidence interval represented by P-value ≤ 0.05 and F-value > \( F_{\text{critical}} \) [90]. In our context, significance denotes the sensitivity of the residual strength with respect to a parametric value change.

Within the chosen parametric range, Table 11 ranks the significant parameters by order of their significance from most to least. This list may be used as a priority list while designing structures. Similarly, Table 12 shows a list of insignificant parameters.
Table 11: Significant parameters for the three structural concepts arranged from most to least.

<table>
<thead>
<tr>
<th>Metal Grillage</th>
<th>Sandwich structure</th>
<th>Stiffened sandwich structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most</td>
<td>Face material</td>
<td>Ply thickness</td>
</tr>
<tr>
<td>Stiffener section modulus</td>
<td>Dense core thickness</td>
<td>Rare core thickness</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>Rare core thickness</td>
<td>Face material</td>
</tr>
<tr>
<td>Stringer section modulus</td>
<td>Ply thickness</td>
<td>Dense core thickness</td>
</tr>
<tr>
<td>Ice Stringer</td>
<td>Core material</td>
<td>Stiffener section modulus</td>
</tr>
<tr>
<td>Least</td>
<td></td>
<td>Ice stiffener</td>
</tr>
<tr>
<td>Stringer spacing</td>
<td>Core material</td>
<td></td>
</tr>
<tr>
<td>Stiffener spacing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 11-Table 12, we may infer the following. For metal grillages,
- There is no significant difference between (a) load falling on a stiffener and (b) in between stiffeners. Pictorially this is represented in Figure 35.

Figure 35: Pressure acts on a plate (a) centred on a stiffener and (b) between two stiffeners.
- There is a significant increase in residual strength if an ice stringer is present.
- Among stringers, most of the strength contribution comes from the ice stringer.

For sandwich structures,
- The dense core materials has no significant difference in residual strength contribution. However, PVC cores performed better in terms of core shear performance.
- There is no significant difference in residual strength between ply configurations.

For stiffened sandwich structures,
- There is no significant difference between load falling on the stiffener or in between stiffeners.

Further insights and inferences can be found in Paper E [7].
4.2.3 Parametric trends

The parametric trends help us pick suitable parametric ranges and understand sensitivity at different parametric levels. Red circles are indicated to highlight parametric values where stress safety factor (SSF) sensitivity is low, and one can opt for the lighter parametric option. Figure 36 shows metal grillages, Figure 37 shows sandwich structures and Figure 38 shows stiffened sandwich structures.

**Figure 36**: Parametric trend of significant parameters for the metal grillage.

**Figure 37**: Parametric trends of significant parameters for the sandwich structure.

**Figure 38**: Parametric trends of significant parameters for the stiffened sandwich structure.
During the identification of parametric trends, we observed parametric interactions for the stiffened sandwich structure \([91]\). No interactions were observed for the metal grillage and sandwich structure. The investigation was performed using a \(2^n\) factorial design of experiment (DOE) method.

In the next section, we look at structural concepts suitable towards impact loading.

### 4.3 Lightweight concepts suitable for impact

There are several structural concepts discussed in literature that may be suitable under impact scenarios. For our analysis, we choose five concepts – metal grillage, FRP composites (conventional and bouligand), metal FRP composites, stiff-tough composites and stiff-tough-viscoelastic composites shown in Figure 39. These are chosen with inspiration from the prevalent state of the art in marine construction and ideas acquired from nature including woodpecker drumming motion [92], bighorn sheep horns [93] and stomatopod clubs [94].

![Figure 39: Structural concepts under investigation for impact arranged in descending order of masses. They are metal grillages, metal-rubber-ceramic composite, metal-ceramic composite, FRP-metal composite and FRP.](image)

The parametrizations of the 5 concepts are compiled in Table 13.

<table>
<thead>
<tr>
<th>Structural concept</th>
<th>Structural element</th>
<th>Variants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metal Grillage</strong></td>
<td>Plate thickness</td>
<td>10, 15, 20 mm</td>
</tr>
<tr>
<td></td>
<td>Stiffener spacing</td>
<td>0.25, 0.5, 0.67 m</td>
</tr>
<tr>
<td></td>
<td>Stringer spacing</td>
<td>0.5, 0.67, 1 m</td>
</tr>
<tr>
<td></td>
<td>Ice stringer/stiffener</td>
<td>Yes, No</td>
</tr>
<tr>
<td></td>
<td>Stiffener elastic section modulus</td>
<td>18.4, 57.3, 94.8 cm(^3)</td>
</tr>
<tr>
<td></td>
<td>Stringer elastic section modulus</td>
<td>150, 303, 443 cm(^3)</td>
</tr>
<tr>
<td></td>
<td>Materials</td>
<td>Steel, Aluminium</td>
</tr>
<tr>
<td><strong>Bouligand FRP Composite</strong></td>
<td>Face ply thickness</td>
<td>0.3, 0.5, 0.7 mm</td>
</tr>
<tr>
<td></td>
<td>Bouligand pitch angles between progressive face sheets</td>
<td>(10^\circ - 20^\circ (interval \ of \ 2^\circ), 25^\circ)</td>
</tr>
<tr>
<td></td>
<td>Number of face sheets</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Face materials</td>
<td>Carbon fibre UD 235, Carbon fibre UD 395, Carbon fibre 395 woven, E-glass</td>
</tr>
<tr>
<td>Conventional FRP composite</td>
<td>Face ply thickness</td>
<td>0.3, 0.5, 0.7 mm</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------------------</td>
<td>------------------</td>
</tr>
<tr>
<td></td>
<td>Ply orientation</td>
<td>([+45/−45]_8); ([+90/0]_8); quasi-isotropic</td>
</tr>
<tr>
<td></td>
<td>Number of face sheets</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Face materials</td>
<td>Carbon fibre UD 235, Carbon fibre UD 395, Carbon fibre 395 woven, E-glass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stiff – Tough composite</th>
<th>Total plate thickness</th>
<th>20, 30, 40, 50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stiff: Tough thickness ratio</td>
<td>4:1, 2:1, 1:1, 1:2, 1:4</td>
</tr>
<tr>
<td></td>
<td>Plate orientation</td>
<td>Stiff plate first, Tough plate first</td>
</tr>
<tr>
<td></td>
<td>Stiff plate material</td>
<td>Boron Carbide, Silicon Carbide</td>
</tr>
<tr>
<td></td>
<td>Tough plate material</td>
<td>Steel, Aluminium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metal - FRP composite</th>
<th>Face ply thickness</th>
<th>0.3, 0.5, 0.7 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metal thickness</td>
<td>5, 10, 15 mm</td>
</tr>
<tr>
<td></td>
<td>Ply orientation</td>
<td>best bouligand, best conventional</td>
</tr>
<tr>
<td></td>
<td>Face material</td>
<td>C395UD, C395 woven, E-glass</td>
</tr>
<tr>
<td></td>
<td>Metal material</td>
<td>Steel, Titanium-alloy, Aluminium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Viscoelastic – tough-stiff composite</th>
<th>Viscoelastic layer thickness</th>
<th>0.01, 0.02 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plate orientation</td>
<td>Ceramic-rubber-metal, Rubber-ceramic-metal</td>
</tr>
<tr>
<td></td>
<td>Tough layer thickness</td>
<td>0.01 m</td>
</tr>
<tr>
<td></td>
<td>Stiff layer thickness</td>
<td>6 mm to 14 mm</td>
</tr>
<tr>
<td></td>
<td>Viscoelastic layer material</td>
<td>Chloroprene rubber</td>
</tr>
<tr>
<td></td>
<td>Stiff layer material</td>
<td>SiC</td>
</tr>
<tr>
<td></td>
<td>Tough layer material</td>
<td>Structural Steel</td>
</tr>
</tbody>
</table>

We use LS-DYNA v 4.7.7 to simulate structural behaviour. For the analysis, we assume a rigid body impactor. The impactor’s dimensions are chosen such that the impact pressure would resemble the maximum compressive strength of ice observed during field trials (~38 MPa [46]). The impact velocity is taken as the vessel’s advance speed (~6 knots) assuming the hull face is perpendicular to the relative velocity vector. The impactor geometry and impact setup are shown in Figure 40. The dimensions of the impactor are shown in Table 14.

(a) [Impact model setup and boundary conditions (BCs)]
(b) [Rigid body impactor geometry]

**Figure 40:** (a) Impact model setup and boundary conditions (BCs) (b) Rigid body impactor geometry.
Table 14: Geometric details of the rigid body impactor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of impact</td>
<td>~0.01 m$^2$</td>
</tr>
<tr>
<td>Length of indenter</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Mass</td>
<td>42.4 kg</td>
</tr>
<tr>
<td>Mean impact stress</td>
<td>~40 MPa</td>
</tr>
<tr>
<td>Velocity (x, y, normal)</td>
<td>(0, 0, 6) kts</td>
</tr>
</tbody>
</table>

We are interested in three outcomes from this study, similar to the quasi-static study.

- Overall comparison of the three concepts for (a) strength and (b) stiffness with respect to mass.
- Significant parameters.
- Parametric trends.

4.3.1 Overall comparison

The residual SSF against mass for the five concepts is shown in Figure 41. The FRP composites are the lightest and its SSF ranges between 1-4. Among them, the bouligand composites have a slight edge. The aluminium grillage is the next lightest alternative. It is closely followed by a metal-FRP composite. The ceramic-metal composites and ceramic-viscoelastic-metal composites do not meet the strength requirements. But the addition of a viscoelastic layer is seen to increase the impact resistance by up to ~2.5 times. The heaviest of all options is the steel grillage.

![Figure 41: Comparison of SSF with respect to mass for all structural concepts investigated for impact.](image)

From this comparison, the FRP composites appear appealing. But they are susceptible to barely visible impact damage (BVID) that can significantly reduce the residual strength [95-97]. In addition, high local pressures can lead to punctures [98]. In such a scenario, the aluminium grillage might seem appealing. But high strain rates from local high pressures can lead to large plastic deformations that would affect the vessel's resistance. A safe solution...
in such a case would be the metal-FRP composite that is comparable in weight with the aluminium grillage and offers better protection.

Strength was found to be more critical than stiffness. Interested readers may refer to Paper E [8] for comparison between structures. Next, we identify significant parameters. This will contribute towards tailoring of the structure for maximum strength/mass ratio.

### 4.3.2 Significant parameters

Within the investigated parametric range, Table 15 ranks the significant parameters by order of their significance from most to least. Similarly, Table 16 shows a list of insignificant parameters.

**Table 15**: Significant parameters for the six structural concepts for impact arranged by order of significance.

<table>
<thead>
<tr>
<th>Steel Grillage</th>
<th>Aluminium Grillage</th>
<th>FRP Composite</th>
<th>Metal-FRP Composite</th>
<th>Metal-Ceramic Composite</th>
<th>Metal-Ceramic-Viscoelastic Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most</td>
<td>Stiffener section modulus</td>
<td>Ice Stringer</td>
<td>Face material FRP material</td>
<td>Metal material</td>
<td>Projectile speed</td>
</tr>
<tr>
<td></td>
<td>Stringer section modulus</td>
<td>Plate thickness</td>
<td>Ply thickness</td>
<td>Metal material</td>
<td>Ceramic material</td>
</tr>
<tr>
<td></td>
<td>Ice Stringer</td>
<td>Stringer section modulus</td>
<td></td>
<td></td>
<td>Viscoelastic layer thickness</td>
</tr>
<tr>
<td>Least</td>
<td>Ice Stiffener</td>
<td>Stiffener section modulus</td>
<td></td>
<td></td>
<td>Orientation</td>
</tr>
</tbody>
</table>

**Table 16**: Insignificant parameters for the six structural concepts tested for impact.

<table>
<thead>
<tr>
<th>Steel Grillage</th>
<th>Aluminium Grillage</th>
<th>FRP Composite</th>
<th>Metal-FRP Composite</th>
<th>Metal-Ceramic Composite</th>
<th>Metal-Ceramic-Viscoelastic Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate thickness</td>
<td>Ice stiffener</td>
<td>Ply angle</td>
<td>Metal thickness</td>
<td>Thickness</td>
<td>Thickness ratio - ceramic: metal</td>
</tr>
<tr>
<td>Stringer spacing</td>
<td>Stringer spacing</td>
<td></td>
<td>Ply orientation</td>
<td>Thickness ratio</td>
<td></td>
</tr>
<tr>
<td>Stiffener spacing</td>
<td>Stiffener spacing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From these tables we infer the following. For metal grillages,

- There is a significant difference in impact behaviour between stiff and flexible grillages. This has also been observed in literature [39].
- Impact predominantly affects local structural design.
- There is no significant difference between load falling on a stiffener or in between stiffeners for stiff grillage (See Figure 35). But the observation is reversed for a flexible grillage.
- The impact is largely borne by the ice stringer.
• Stringer and stiffener section moduli are significant for both grillages, but the order of significance is different. For stiff plates, the stringer modulus is more significant.

For FRP composites,
• There is no significant difference between conventional and bouligand ply configurations.
• There is a significant difference between UD and woven fabrics for the Bouligand configuration only.
• The difference in significance between carbon fibre 230UD and carbon fibre 395UD is ~10 times larger for Bouligand configuration than for conventional configuration.
• The difference in significance between glass fibre and carbon fibre is much more pronounced for conventional configuration than for bouligand configuration.

For Metal FRP composites,
• The strength is not influenced by geometric parameters. Only respective materials influence strength.
• The FRP’s performance is not influenced by the metal material and vice versa.
• There is a significant difference between UD and woven face sheets.

For Metal-Ceramic composites
• The ceramic is sensitive to its relative arrangement to metal layer whereas the metal behaves similarly in both arrangements.
• The ceramic material has no influence on the metal’s SSF whereas the metal material has a significant influence on the ceramic’s SSF (only for the orientation - ceramic: metal).
• The ceramic failure mechanism is independent of its thickness due to its brittle nature.

For Ceramic-Viscoelastic-Metal composite
• Addition of a viscoelastic layer has a significant improvement in impact performance.
• At 6 knots, there is no statistical significance between the relative positions of viscoelastic layer and ceramic layer (provided metal layer is placed last). This is represented in Figure 42.

![Figure 42](image)

**Figure 42:** Representation of the two orientations for the composite (a) ceramic - viscoelastic - metal and (b) viscoelastic - ceramic - metal.

• At 10 knots, the ceramic-viscoelastic-metal configuration has a 50% higher ceramic and metal SSF in comparison with viscoelastic-ceramic-metal configuration.
• A high $t_{\text{ceramic}}/t_{\text{viscoelastic}}$ ratio favours the ceramic while a low ratio favours the metal, where $t$ is layer thickness.
4.3.3 Parametric trends

The parametric trends help us pick suitable parametric ranges and understand sensitivity at different parametric levels. Red ellipses indicate parametric values where SSF sensitivity is low, and one can opt for the lighter parametric option. Figure 43 shows metal grillages, Figure 44 shows Bouligand FRP, Figure 45 shows conventional FRPs and Figure 46 shows metal-FRP composites.

**Figure 43:** Parametric trends of significant parameters for the Steel and Aluminium metal grillage. Red ellipses indicate potential areas for saving weight.

**Figure 44:** Parametric trends of significant factors for the Bouligand composite.

**Figure 45:** Parametric trends of significant factors for the Conventional composite.
Now we have compared different structural concepts that are suitable for (a) quasi-static loading and (b) dynamic impact loading. This gives us a wide parametric range of suitable candidates that can be used to develop a lightweight ice-going hull structure. In the next section, we compare all the concepts presented here from the perspective of life cycle costs, energy and emissions.

### 4.4 Life cycle analysis (LCA)

All materials and structural concepts investigated so far are compared in the life cycle analysis. For the comparison, the lightest successful variants are considered, and their respective scantlings and masses are used in calculations. Table 17 shows a list of forming techniques that are used in the analysis.

In general, the scales of energy and costs follow the trend:

*Material manufacturing >> Structure manufacturing > Disposal phase.*

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacture Primary Process</th>
<th>Secondary Process</th>
<th>Recycling Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Steel</td>
<td>Roll forming</td>
<td>Fine machining</td>
<td>Recycle [99]</td>
</tr>
<tr>
<td>Aluminium Alloy</td>
<td>Casting</td>
<td>Fine machining</td>
<td>Recycle [100]</td>
</tr>
<tr>
<td>Titanium Alloy</td>
<td>Roll forming</td>
<td>Fine machining</td>
<td>Recycle [101]</td>
</tr>
<tr>
<td>Carbon Fibre</td>
<td>Fabric production</td>
<td>Cutting and trimming</td>
<td>Pyrolysis [102]</td>
</tr>
<tr>
<td>E-Glass</td>
<td>Fabric production</td>
<td>Cutting and trimming</td>
<td>Downcycle [103]</td>
</tr>
<tr>
<td>PVC</td>
<td>Polymer extrusion</td>
<td>Cutting and trimming</td>
<td>Downcycle [104]</td>
</tr>
<tr>
<td>PET</td>
<td>Polymer extrusion</td>
<td>Cutting and trimming</td>
<td>Downcycle [105]</td>
</tr>
<tr>
<td>Chloroprene rubber</td>
<td>Polymer molding</td>
<td>Cutting and trimming</td>
<td>Downcycle [106]</td>
</tr>
<tr>
<td>SiC</td>
<td>Acheson process</td>
<td>Grinding</td>
<td>Downcycle [107]</td>
</tr>
<tr>
<td>BC</td>
<td>Heat resistance furnace process</td>
<td>Grinding</td>
<td>Downcycle [108]</td>
</tr>
</tbody>
</table>
4.4.1 Quasi-static resistant candidates

Energy and CO₂

The manufacturing and disposal phases are compared in Figure 47. The best (black) and worst (red) cases are highlighted.

Some observations are,

- Metal grillage: Steel is better than aluminium alloy.
- Face sheets: E-glass is better than carbon fibre during material manufacture phase. The trend reverses for structure manufacture and disposal phases.
- Carbon fibre face sheets: C230 produces ~half CO₂ emissions than C395.
- Core materials: PVC is better than PET.
- End of life (EoL) recovery: Metal grillages are the best.

\[\text{Metal grillage: Steel is better than aluminium alloy.}\]
\[\text{Face sheets: E-glass is better than carbon fibre during material manufacture phase. The trend reverses for structure manufacture and disposal phases.}\]
\[\text{Carbon fibre face sheets: C230 produces ~half CO₂ emissions than C395.}\]
\[\text{Core materials: PVC is better than PET.}\]
\[\text{End of life (EoL) recovery: Metal grillages are the best.}\]

\[\text{Figure 47: Comparison of life cycle energy consumption (vertical bars) and CO₂ emissions (black dots) averaged over a year for quasi-static resistant pool of structural concepts. Metal grillages are shown in black, sandwich structures in red and stiffened sandwich structures in blue.}\]
Cost
We compare the life cycle costs in Figure 48. The best (black) and the worst (red) combinations are highlighted.

Some observations are,

- Material cost: Stiffened sandwich > sandwich structure > metal grillage.
- Metal grillages: structural steel has a higher structure manufacturing and disposal cost than aluminium alloy. Both have similar material costs.
- Face material: Sandwich structures with C230 and C395 are similar.
- Core material: PVC is ~10% more expensive than PET.

**Figure 48**: Comparison of life cycle costs averaged over a year of quasi-static resistant pool of structural concepts. Metal grillages are shown in black, sandwich structures in red and stiffened sandwich structures in blue.
### 4.4.2 Impact resistant candidates

*Energy and CO₂*

The best (black) and the worst (red) combinations are highlighted in Figure 49.

Some observations are,

- Titanium alloys have the highest energy consumption during the material manufacturing phase while E-glass has the least.
- FRP materials: Carbon fibre variants have higher material manufacturing emissions than E-glass.
- Disposal phase: Structural steel is the most energy and emission intensive while FRP composites are the least.
- The EoL for FRP composite emissions are positive due to a lack of effective recycling techniques and one has to rely on pyrolysis.

**Figure 49:** Comparison of life cycle energy consumption (vertical bars) and CO₂ emissions (black dots) averaged over a year for impact resistant pool of structural concepts. Metal grillages are shown in black, FRP in red, metal-FRP in yellow, Ceramic-metal composite in blue and Ceramic-viscoelastic-metal in dark blue.
Cost
We compare the life cycle costs for these variants in Figure 50. The best (black) and the worst (red) combinations are highlighted.

Some observations are,

- **Material Cost**: metal-FRP composites > ceramic-metal > FRP > metal grillages.
- **Metals**: Titanium alloy has significantly higher material manufacturing cost than other metals. Aluminium is ~2 times more expensive than steel.
- **During the structure manufacturing phase**, the costs of material variants within structural concepts are largely similar.
- **During the disposal phase**, structural steel has the largest cost.

**Figure 50**: Comparison of life cycle costs averaged over a year of impact resistant pool of structural concepts. Metal grillages are shown in black, FRP in red, metal-FRP in yellow, Ceramic-metal composite in blue and Ceramic-viscoelastic-metal in dark blue.
4.5 Concluding remarks

We noted that a lightweight ice going hull is of immense advantage in reducing emissions and increasing payload capacity in regions with seasonal ice cover. A survivability study of the current state of the art ice classed barge showed significant reserve strength assuming quasi-static loading and allowance for plastic deformations. The study also showed the possibility of operating a non-ice barge in light ice conditions without catastrophic failure. This established the possibility for weight reduction in steel grillages and exploration of alternate structural concepts.

For quasi-static loading, the stiffened sandwich showed most promise offering light weight as well as a high gross tonnage. The parametric studies found that an ice stringer has a high influence in reducing the structural weight. Within materials, both PET and PVC performed similarly with sandwich structures however PVC displayed superior core shear performance. Among face sheets, C230 UD fibres showed promise. Based on LCA, C230-PET has the least energy and CO₂ footprint while metal grillages were the least expensive.

For impact loading, the metal-bouligand FRP composite showed the most potential in offering a lower mass as well as protection against impact damage. A less expensive viable alternative was the aluminium grillage, though it is prone to plastic deformations. Based on LCA, FRP displayed the least energy and CO₂ footprint. The metal-FRP composite showed the highest energy and CO₂ footprint as well as being the most expensive option.
Chapter 5
A Lightweight Ice-going Hull

5.1 Introduction

So far, we have looked at different ice-hull interaction scenarios, ice load estimation techniques and structural response of concepts and materials. In this chapter we combine the gained knowledge into designing a lightweight hull structural concept for ice operations.

Our target hull should be robust against the three types of loading introduced in Chapter 3 (Figure 20). While doing so, it should be lighter than prevalent steel hulls. To test the reliability of concepts, the loading scenarios need to be reasonably realistic.

We start by proposing the template for a lightweight hull structure concept. Next, we develop a (a) quasi-static loading representation and (b) an impact model representative of freshwater ice. The models are validated with experimental data. Then, suitable candidates are chosen from the parametric study in Chapter 4 and applied to the proposed hull structure template. From WPT's perspective, a lightweight hull will result in reducing hull resistance in non-ice conditions and have a higher payload capacity.

5.2 The tri-layer concept: lightweight hull structural template

Assuming thin first year ice conditions in sheltered waters, typically found in the Lake Mälaren region, ice interactions are limited to level ice and impact with small ice floes (see Figure 19(c)). In Chapter 3, we noted for level ice, three types of interaction - quasi-static pressure loads arising from ice crushing and dynamic loads from impact, spalling and material extrusion [60] and abrasion loads from ice scraping. Keeping these forces in mind, a template for a lightweight hull structure is proposed in Figure 51.

The structural concept consists of three representative layers where the outermost layer is abrasion resistant (L1), the layer underneath is impact resistant (L2) and the innermost layer is resilient to large quasi-static pressures (L3).
The proposed structural concept for an ice-going hull consists of 3 layers representative of quasi-static loads, impact loads and abrasion loads.

On initial impact with level ice, layer L2 absorbs or disperses the impulsive loads. Thereafter, the contact pressure increases as we observe crushing of the ice sheet against the hull. These resulting pressures (nominal and HPZ) are borne by layer L3. Once the ice breaks, we observe impulse forces arising from spalling and material extrusion which are again borne by L2. The broken ice pieces are pushed under the hull and scrape against the hull. The resulting abrasive forces are borne by layer L1.

In Chapter 4, we saw structural concepts that fulfil requirements for layers L2 and L3. Among these, the stiffened sandwich structure (L3) and Bouligand metal-FRP (L2) were the most favourable candidates. Candidates for layer L1 are not investigated here but potential candidates like pseudo-elastic wear resistant materials have been discussed in literature [109]. A composite ensemble of these layers will be a suitable lightweight hull structure within the current scope of investigation.

To investigate and validate the concept, we first establish reasonable loading scenarios. For this, we propose a quasi-static loading schematic inspired from experimental observations on load distribution. Then, we develop an experimentally validated cohesive zone method (CZM) model to represent ice impact.

### 5.3 Quasi-static loading model

A realistic distribution of loading on the hull, observed during field trials is shown in Figure 52. To mimic this, we divide the loading area into a grid of 3 x 10 cells such that each cell has an area of 0.01 m² corresponding to HPZ for Lake Mälaren (see Figure 53). Across the cells, we apply a pressure load that is normally distributed for a peak of 5.7 MPa and mean of 2.6 MPa, representative of local conditions [5].
**Figure 52**: Observed FSICR load distribution on a panel. The load can be idealized as rectangular blocks on square loading areas.

<table>
<thead>
<tr>
<th>X1</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>E1</th>
<th>F1</th>
<th>G1</th>
<th>H1</th>
<th>I1</th>
<th>J1</th>
</tr>
</thead>
<tbody>
<tr>
<td>X2</td>
<td>A2</td>
<td>B2</td>
<td>C2</td>
<td>D2</td>
<td>E2</td>
<td>F2</td>
<td>G2</td>
<td>H2</td>
<td>I2</td>
<td>J2</td>
</tr>
<tr>
<td>X3</td>
<td>A3</td>
<td>B3</td>
<td>C3</td>
<td>D3</td>
<td>E3</td>
<td>F3</td>
<td>G3</td>
<td>H3</td>
<td>I3</td>
<td>J3</td>
</tr>
</tbody>
</table>

**Figure 53**: Mimicry of the representative load distribution on a panel.

Five sets of loads are applied in five time-steps as shown in Figure 54. Each time-step is normally distributed and stochastically arranged. The outer layers (X1, X3) have a lower intensity as compared to the middle layer (X2).

**Figure 54**: Quasi-static load distribution on the panel over 5 sequential time steps. The loading area corresponds to Figure 53.
In the next section, we will assemble candidates for the tri-layer structural concept and study them under quasi-static and impact response.

5.4 CZM impact model

The CZM method has been previously used to simulate the behaviour of brittle ice impact in literature [39, 110-112]. The method uses the traction separation law to simulate the failure of elements when a critical inter-element separation distance is reached. A delamination composite model (MAT138) is chosen to associate inelastic deformation of elements with crack formation [113]. Delamination is represented by compressive and tensile failure criteria.

![CZM model of the ice impactor](image)

**Figure 55:** A CZM model of the ice impactor. Bulk (black) and cohesive (white) elements are shown.

The ice model is developed by creating a tetrahedral mesh of solid elements representing the properties of ice. In between the elements, zero thickness cohesive elements are introduced (see Figure 55). These elements facilitate crack initiation and propagation. The additional mass arising from the introduction of cohesive elements is compensated by adjusting the density of the solid elements as,

\[
\rho_s' = (1 - f_m)\rho_{\text{real}}
\]

where, \(f_m\) is the mass ratio between cohesive and solid elements and \(\rho_{\text{real}}\) is the density of ice.

Additionally, the stiffness of the solid and cohesive elements are adjusted to compensate for artificial compliance [114] as,

\[
E_s' = E_s \left(1 - \frac{1}{f_k}\right)^{-1}
\]

\[
E_{CZ} = \frac{f_k t_{CZ} E_s'}{0.5L_s}
\]

where, \(f_k\) is the stiffness ratio, \(t_{CZ}\) is the artificial thickness and \(L_s\) is the element length.
The geometry of the ice impactor is taken to reflect conditions in Stockholm. Its mass is calculated using the ice breaking length \([52]\), ice thickness and floe wedge angle. The geometry is given a conical shape as shown in Figure 55 so that an entire range of contact areas and pressures may be captured. The geometric parameters are shown in Table 18.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>203 mm</td>
</tr>
<tr>
<td>Height</td>
<td>350 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>224 kg</td>
</tr>
<tr>
<td>Cone angle</td>
<td>30°</td>
</tr>
</tbody>
</table>

### 5.4.1 Model validation with metal grillage

Ice drop tests were performed on an aluminium plate in TUHH, Hamburg [81]. The setup was replicated in LS Dyna using the developed ice model. The force comparison between experiments and simulations shows good agreement in terms of force duration, shape and peak (see Figure 56). However, the model overestimates the peak by 5 kN.

![Figure 56: Comparison of impact force on an experimental and FEM model for an Aluminium Grillage.](image)

The pictorial evolution of panel-ice impact between experimental and FEM model is shown in Figure 57.
5.4.2 Model validation with sandwich structure

KTH in collaboration with TUHH performed ice drop tests on carbon fibre-PVC sandwich panels. For an impact speed of 1.5 m/s, forces on the sandwich panel are recorded. The comparison of forces on the plate shows two characteristic peaks, as seen in Figure 58. The simulation model overestimates the experimental model by 5 kN, comparable to that observed with the aluminium grillage.

A comparison of experimental and simulation model behaviour shows similar evolutions (see Figure 59).
5.5 Candidates for the tri-layer concept

The most suitable parametric combinations of candidates for layers L2 and L3 are combined (see Table 19). These are an aluminium grillage, a stiffened sandwich and a metal-FRP stiffened sandwich structure.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Structural concept</th>
<th>Layers of tri-layer concept</th>
<th>Mass</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A</td>
<td>Grillage</td>
<td>Aluminium grillage</td>
<td>495</td>
<td>Al - alloy</td>
</tr>
<tr>
<td>Panel B</td>
<td>FRP Stiffened</td>
<td>Bouligand 20° FRP</td>
<td>404</td>
<td>C395UD, PVC200</td>
</tr>
<tr>
<td>Panel C</td>
<td>Stiffened sandwich</td>
<td>Metal- Bouligand 20° FRP</td>
<td>492</td>
<td>Ti - alloy,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composite</td>
<td></td>
<td>C395UD, PVC200</td>
</tr>
</tbody>
</table>

The three structural concepts are investigated for quasi-static and impact response.

5.5.1 Quasi-static response

The three panels are subjected to the quasi-static loading model proposed earlier. Figure 60(a) compares the deformations. We find, Panel C is the stiffest of the three options. Its magnitude is \(\sim 4\) times lesser than Panel B. The large deformation of Panel B can be attributed to its Bouligand ply arrangement, which makes it behave like a spring coil [7].
residual stresses are compared in the form of inverse reserve factors in Figure 60 (b). We notice that Panel A only just enters the plastic region while both panels B and C show sufficient reserve strength. Panel C has the best performance, which can be attributed to the addition of Titanium alloy.

![Comparison of quasi-static performance of the three concepts.](image)

**5.5.2 Impact response**

The three panels are subjected to the ice model representative of freshwater ice. We observe that deformation is not critical under impact scenarios. The oscillation magnitudes are under 0.5 mm. The residual strength in the contact area for the three panels are compared in Figure 61. Panel C performed the best and recorded the lowest stresses. Panel A performs reasonably well and the stress falls within tolerance levels. However, the impact pressure was noted to be quite high. This may result in permanent sets on impact. Panel B performed well at the design speed with over 40% reserve strength. However, it was observed to be susceptible to failure at higher speeds.

![Comparison of strength for the three concepts subjected to impact loading at 3 knots.](image)

*(The X axis shows a normalized time scale).*
5.6 Concluding remarks

A tri-layer structural concept is proposed to withstand the predominant types of loading, that are observed during ice-hull interaction. Several candidates, that were explored in Chapter 4, can fulfil the layers requirements. To validate them using realistic loading scenarios, we proposed a quasi-static loading model and an ice impact model. Given the highly stochastic nature of ice, these models are valid only in specific ice conditions. But there is scope for calibrating the models with experiments involving other types of ice. Using the developed loading models, three candidates for the tri-layer concept are presented. The aluminium grillage has the advantage of a well-established state of the art in construction and low cost but prone to plastic deformations. The FRP sandwich has the advantage of low mass but is prone to failure at high speeds. Finally, metal-FRP sandwich has the advantage of robustness against both loading types, but it has a relatively high mass, environmental impact and high manufacturing cost. These concepts need to be experimentally validated before conclusions on applicability can be drawn.
Chapter 6
Conclusions and Future Work

Waterborne public transportation (WPT) has been gaining popularity over the past decade. Despite the potential and interest, many questions still remain unanswered when viewing WPT as a transport option. The lingering reluctance in the minds of public transport providers (PTPs) remain. But slowly the solutions are beginning to unravel, and we are inching towards sustainable operations.

The thesis was centred around answering the fundamental questions posed in the research objectives. The following paragraphs tackle these questions and identify broad conclusions. This is followed by identifying the scope for future work.

9.1. Conclusions

WPT challenges

Seven primary areas of interest were identified when describing WPT. These are – route type; scheduling; transit network integration; terminal location, design and infrastructure; passenger perception; ferry designs, and operational costs and environmental impact. They represent the start for any PTP when they think about implementing WPT. It was found to be tactical to divide the challenges as regulatory and technical, so that one may adopt an appropriate strategy. Primary regulatory challenges are funding constraints, competition from other modes, lack of political will and lack of legislation. Primary technical challenges relate to design practices that limit cost and time efficient production of tailored ferries, ice operations and terminal design.

The commuter ferry platform

One of the key observations of WPT is a stark absence of ferry design standardization around the world. On studying the routes taken by ferries under WPT, three standard types were identified – city, bridge and suburban. It was found that ferries have broadly similar design requirements for each of these route types. To cater for differences in between them, a three-stage operational requirements structure was proposed. The structure goes from broad design in the first stage characterized by the route type, followed by rule-based design in the second stage and performance optimisation in the third stage. The structure will help overcome differences arising from subjective interpretation of design between stakeholders.
Considering contemporary trends of WPT vessels, local PTP requirements and transport modelling, two standard ferry sizes are proposed. Platform architecture was effective in creating a family of ferries that are economical, have large variants and quick to manufacture. To accommodate customization, driven by the local operational requirements, modularization was adopted. Function structure heuristics (FSH) was the most suitable strategy in identifying five standard module groups and respective dimensions. Different combinations of modules ensure multiple ferry variations and tailoring potential. The commuter ferry platform is expressed as a potential solution through examples in several cities.

**Holistic ferry evaluation**

A practical challenge that a PTP might face is – ‘how to choose the most suitable ferry’. In the case of a commuter ferry platform, how to choose the optimal combination of modules. To help answer this, a framework for quantifying the operational requirements was developed. For the tertiary level, economic and environmental performance metrics were made objective based on currency value and emission quantities. The subjective nature of social performance was made objective through proposed assessment rules, inspired by passenger surveys and literature. The use of the evaluation system is identified under 4 scenarios: (a) in shipyards during new constructions; (b) to identify most appropriate modules in a modular ferry; (c) for comparing vessels available for purchase and (d) for identifying strengths and weaknesses of the existing fleet.

The proposed system can lead to objective decision making, resulting in the most suitable ferry that is tailored towards local requirements. It is presented as a user-friendly tool for PTPs.

**Operating in freshwater ice conditions**

One of the foremost technical challenges typical of the Stockholm region is ice navigation. The existing fleet cannot operate in ice during winter months due to the risk of catastrophe, arising from the large structural loads. If one could estimate these loads, an appropriate ferry may be designed. But the complex nature of ice, large differences in local properties and the stochastic nature of ice-hull interaction makes it difficult to have analytical models. Further, there is an absence of experimental data in freshwater ice conditions. To overcome these limitations, a probabilistic approach using light sea-ice datasets that is adjusted to local conditions was developed. The predictions fell within the range of values calculated using analytical and rule-based design predictions. The uncertainty involved was calculated using variation mode and effect analysis (VMEA) approach. It was concluded that experimental validation is necessary. Until then, we may use the state of the art represented by rule-based design.

** Constituents of a lightweight ice going hull**

For WPT, a lightweight ice going hull poses several advantages. Such ferries are comparable in resistance with non-ice going vessels during ice free periods. This would result in lower
emissions as well as lesser fuel expenditure. Further, these ferries can have a larger payload capacity, thus opening the option for battery powered electric propulsion.

The investigation of lightweight hulls is performed by dividing the ice-hull interaction into quasi-static pressure loading, dynamic impact loading and abrasive loading phases. Potential candidates for each loading phase are identified through a literature survey, prevalent state of the art and by observing nature. For quasi-static loading, the stiffened sandwich showed potential, having both low mass as well as a high gross tonnage. The combination of carbon fibre and PVC were favourable from a weight perspective. For impact loading, the Bouligand fibre reinforced plastic (FRP) composite was the lightest alternative. But considering the risk of BVID, metal-FRP composite was considered a safer alternative. A life cycle analysis (LCA) was performed to identify different combinations of materials considering economy and environmental impact. The metal grillages (exception of Titanium alloy) in general were the most environmentally friendly while composites were the least. However, the benefit of a lighter hull and corresponding reduction in hull resistance needs to be borne in mind.

**The tri-layer hull structural concept**

A structural concept consisting of three layers corresponding to the loading phases in a typical ice-hull interaction is envisaged. The best parametric variants found in chapter 4 are applied to the corresponding hypothetical layer to create a lightweight hull. Three promising candidates for the tri-layer concept were identified. To test the candidates under different loading conditions, a stochastic quasi-static loading model and a cohesive zone method (CZM) based impact loading model was developed. Among the candidates, the stiffened sandwich was the lightest but susceptible to failure at higher speeds. The aluminium grillage was the heaviest option but demonstrated good survivability with tendency for plastic behaviour. It was also the most cost and environmentally friendly option. Metal-FRP sandwich showed excellent survivability for both types of loading with no plastic behaviour. However, the structure is expensive, emission-intensive and weighs nearly as much as the aluminium grillage.

**9.2. Future Work**

The thesis explored several questions that riddle WPT today. While the research contributions provide some answers, they also open new doorways and pose fresh questions that may be worth exploring in the future. These are summarised in the following bullets.

- It is of interest to further develop the methodology for modularization of ferries. Future work needs to focus on interface design, structural integrity after modularization, production logistics, costs and integration with classification society rules.
- In the holistic evaluation of ferries, other MCDM methods can be explored that have a fewer number of pair-wise comparisons. This will make it easier for PTPs to use the tool.
• In evaluating design performance index (DPI), the social performance evaluation needs further development through broader surveys performed in multiple cities. It is also of interest to investigate the weight preferences in different cities.

• In the estimation of ice loads in freshwater conditions, there is a need to perform experimental studies so that the probabilistic method’s parameters may be calibrated.

• It would be beneficial to analyse uncertainties related to ice operations using a probabilistic VMEA model.

• In the investigation of lightweight structures, other concepts like fibre-metal laminates (FML) and shear thickening fluid (STF) infused composites are worth exploring.

• Machine learning models in combination with analytical models may be explored using the available data, to reduce reliance on computationally expensive finite element method (FEM).

• For the impact loading model, there is a need for experimental validation of newer novel concepts such as Bouligand FRP and metal-FRP composites.

• In this thesis, passive ice navigation strategies were explored that relied on the vessel’s structural strength and form. In the future, active ice breaking strategies may be explored where ice is broken using alternate techniques. This will help in overcoming one’s dependence on hull strengthening as the only solution.

This concludes the thesis. It is my sincere hope that this is a small step towards a more sustainable future.

Thank you for taking the time in reading this work.
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Appended Papers