IIIEE Theses 2020: 40

PUTTING A NEW SPIN ON SHIPPING

Mapping the Flettner Rotor Innovation System and Exploring Human Factors in Operation

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Thesis for the fulfilment of the
Master of Science in Environmental Sciences, Policy & Management (MESPOM)
jointly operated by Lund University – University of Manchester -
University of the Aegean – Central European University

Lund, Sweden, June 2020

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfilment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

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Published in 2016 by IIIEE, Lund University, P.O. Box 196, S-221 00 LUND, Sweden,
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ISSN 1401-9191

Acknowledgements

First of all, I would like to say a great big thank you to all those who helped me with the early formulation and planning of this thesis: Thanasis Kizos and Oksana Mont for their early input in proposing interesting avenues to explore and narrowing the scope enough to begin planning; Thomas Lindqvist in his expertise in pinpointing IIIEE alumni and faculty to steer me towards the relevant people, and Sarah Zinetti in providing wise guidance and much inspiration from her wonderful thesis on another fascinating maritime decarbonisation technology, cold ironing.

My most heartfelt gratitude is reserved for my diligent supervisors, Nicole Costa, Vendela Santén and Åke Thidell, who have tirelessly and selflessly offered me their valuable time and expertise in making this work possible. I am very grateful for all you have taught me and for offering me the opportunity to dive into a world I find so interesting and exciting.

Next, I'd like to thank my wonderful friends in MESPOM and EMP and all the others met along the way who brought so much joy and fond memories through rain and shine during our magnificent times in Budapest, Lesvos and Lund. It will be hard to top the exciting adventures we have had together, especially with Charlie and Tom, and I look forward to our eventual and much-awaited graduation party!

I would like to extend my sincere gratitude to all the knowledgeable interviewees who provided their expert insight into the world of Flettner rotors, without whom this study would not exist. I'd especially like to thank the entire crew of the *M/S Viking Grace* for their generous hospitality and giving me the fascinating opportunity to visit their beautiful ship and observe its inner workings.

Lastly, but by no means least, I am eternally grateful to my family for their belief in me, their loving words of encouragement and unending devotion to my education. Our shared love of cooking and travelling ensured I always felt at home when far away. Thank you for being there to advise me throughout this degree with your unique perspectives and experiences and especially for homely comforts during the stranger days of 2020.

Abstract

This thesis concerns Flettner rotors, a wind propulsion technology for commercial shipping which has recently gained momentum due to its ability to reduce fuel consumption, and consequently CO_2 emissions, in a polluting sector of industry. Flettner rotors are able to reduce average fuel consumption by up to 20% and can be operated on a wide variety of ship types and sizes through both retrofit and installations on new builds.

The technology is conceptualised within the complex socio-technical system of maritime operations. Using semi-structured interviews of expert practitioners and document analysis, the state of the current Flettner rotor innovation system is mapped, including organisations, institutions and functions of innovation. A human factors approach is applied to gain data of operational experience, using direct observation of the technology on board a vessel and semi-structured interviews of practitioners, including crew members. This is used to identify the impact of Flettner rotors on vessel operations and the factors that influence Flettner rotor fuel saving performance.

Findings show that the technology is close to commercialisation, but requires appropriate policy intervention to secure its development, such as facilitated access to finance, artificially-increased fuel prices and the incorporation of the maritime transport sector into carbon pricing mechanisms. Furthermore, the Flettner rotor is shown to be easily integrated into existing ship operations for most ship types with minimal increases in crew workload.

Finally, fuel saving performance is found to be highly dependent on human factors, contrary to the beliefs of many technology providers. Improved bridge crew training, more detailed sailing instruction and motivation by shipowners are solutions to reduce fuel consumption in the near-term. Further validation of Flettner rotors and suitable policies to drive decarbonisation will lead to the technology's uptake and incorporation into zero-emissions concepts for future shipping.

Keywords: wind ship propulsion; Flettner rotor; human factors; technological innovation system; operational experience.

Executive Summary

This thesis explores the development and operation of Flettner rotors (FRs), a type of wind propulsion technology to reduce fuel consumption in commercial shipping. Effectively large rotating columns attached to a ship's deck and powered by electricity, the devices harness wind energy to provide substantial auxiliary forward thrust to a vessel, resulting in average fuel consumption reductions of up to 20%, providing shipowners with cost savings and reducing greenhouse gas (GHG) emissions.

The significance of this study is underpinned by the need for rapid decarbonisation and the reduction of air pollutants in the maritime sector. As a sector highly reliant on fossil-fuels, commercial shipping accounted for 3.1% of global GHG emissions in 2012 with a projected growth in emissions of 50-250% by 2050, according to the International Maritime Organization (IMO). Policies to reduce maritime GHG emissions in-line with Paris Agreement goals have, thus far, been inadequate to keep global warming below 1.5-2°C.

A number of promising technologies exist offering reductions in fuel consumption, including a variety of wind propulsion technologies in various stages of development. Of these, FRs are the most mature. As of writing, six vessels operate FRs and two more installations are planned in 2020, more than any other wind propulsion technology. The simple, reliable and proven devices operate automatically and can be retrofitted onto a large number of vessels, enabling near-term reductions in maritime emissions, according to the European Commission.

Despite this, barriers still remain which prevent widespread FR uptake. Research exploring innovation systems of various wind propulsion technologies has identified a number of technical, economic and institutional barriers hindering its commercialisation, but none offer an analysis specific to the case of FRs. Furthermore, the addition of new automated equipment to ships increases the complexity of onboard operations and makes overall system performance more dependent on collaboration and communication between actors.

The objective of this research is to explore the FRs in the context of maritime shipping and prescribe recommendations to industry actors. Two theoretical frameworks are used which apply a systems-thinking approach: technological innovation systems and human factors.

Technological innovation systems theory is used to map the current state of FR innovation, including all identifiable organisations, the network in which they communicate and interact, the relevant political and social institutions and the dynamic functions between them.

Human factors are investigated for the first time in academic FR research, applying the experience and knowledge of those who develop and use the technology to identify solutions to issues relating to FR design, operation and performance.

This resulted in the formulation of the following three research questions:

1. What is the current state of the FR innovation system and how has this evolved?
2. What are the disruptions by FRs to the socio-technical system of vessel operations, according to operational experience?
3. What adjustments to the socio-technical system should be made to optimise FR operation, performance and uptake?

The research was undertaken using several qualitative methods for data collection, depending on the theoretical framework used. Research Question 1, as an innovation systems question, was answered using semi-structured interviews of expert practitioners and analysis of relevant

industry documents. Human factors explored in Research Questions 2 and 3 were answered using a usability assessment, consisting of interviews with experienced crew members and direct observation on the rotor vessel *M/S Viking Grace*, as well as interviews of shipowners and technology providers.

The data was analysed by identifying emergent themes based on categories in theory which were then continuously and iteratively reformulated throughout the research process to reshape and redirect the final outcome and findings.

Firstly, the findings of this thesis present a description of the current state of the FR innovation system, providing the reader with a frame of reference to the various actors involved, and detailed explanations of innovation functions to provide insight for policy makers. It is found that FR uptake can best be stimulated through the introduction of economic policies to reduce shipowner return-of-investment, or payback time. Furthermore, the collaboration and communication of organisations into associations and public-private partnerships increases the chances of accessing resources, protecting interests and influencing policy.

Secondly, findings from operational experience identify that FRs have little or no impact on vessel operations such as navigation, maintenance and cargo handling or that impacts are manageable using relatively inexpensive solutions. Exceptions are inaccessibility to certain waterways due to increased air draught and power availability onboard, potentially limiting the uptake of FRs on retrofits. Nonetheless, solutions to these issues exist and a large number of commercial vessels remain suitable for FR installations.

Furthermore, the usability assessment identified that human factors have an important influence on FR operation and performance, contrary to the beliefs of some technology providers. Fuel savings are shown to be directly influenced by bridge crew attitudes towards, and effective usage of, the technology. Transparent communication between crew members, technology providers and shipowners is vital for the effective operation of FRs and the protection of crew well-being. Fuel saving performance can be improved by introducing comprehensive user-led training programs taught by experienced bridge crew members, improving and increasing the information displayed in user interfaces to better instruct effective fuel consumption reduction and motivating crew to sail efficiently through incentives or competition.

The findings of this thesis produced the following recommendations to different actor groups:

- **Policy makers** should realise that FR and other decarbonisation technologies are at the brink of commercialisation and require market-based interventions, such as carbon pricing, facilitated access to finances and taxes on bunker fuel, in order to provide shipowners with attractive payback times.
- **Technology providers** should focus on improving human factors before implementing technical optimisation solutions. Human factors should be incorporated into the design and operation of FRs by redesigning bridge crew user interfaces to clearly instruct reduction of fuel consumption and creating user-led training programs that instruct effective sailing.
- **Technology users** should understand the value of user experience in developing and improving FR innovation in projects such creating improved training courses for new users, collaborating with research institutes to create comparable performance validation and optimisation, debunking myths about FRs and educating potential shipowners.
- **Potential technology users** should understand the reality of FR operation, based on findings from user experience. Human factors should be considered as key influences

on fuel savings and investments in training appropriate for reducing payback times. Furthermore, the potential for fleet retrofit should be assessed and installations on new builds considered.

A further general recommendation to shipowners and technology providers is to increase connectivity and communication with other actors involved in FRs, join international associations and collaborate in public-private partnerships to improve knowledge transfer and strengthen knowledge development and diffusion in the sector.

Table of Contents

List of Figures

List of Tables

Abbreviations

CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CPP	Controllable Pitch Propellers
dwt	Deadweight tonnage
EEDI	Energy Efficiency Design Index
EIB	European Investment Bank
ERDF	European Regional Development Fund
ETI	Energy Technology Institute
ETS	Emissions Trading Scheme
EU	European Union
F1 to F7	Functions 1 to 7
FR	Flettner Rotor
FRIS	Flettner Rotor Innovation System
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
IEA	International Ergonomics Association
IMO	International Maritime Organization
IWSA	International Windship Association
LDC	Least-Developed Countries
LNG	Liquid Natural Gas
MEPC	Marine Environmental Protection Committee
MGO	Marine Gas Oil
MLP	Multi-Level Perspective
NGO	Non-Governmental Organisation
NO_x	Nitrogen Oxides
PTU	Potential Technology User
R&D	Research & Development
RINA	Royal Institute of Naval Architects
RoPax	Roll-on roll-off passenger vessel
RoRo	Roll-on roll-off freight vessel
SEEMP	Ship Energy Efficiency Management Plan

SIDS	Small-Island Developing States
SO_2	Sulphur Oxide
STS	Socio-Technical System
TIS	Technological Innovation System
TP	Technology Provider
TU	Technology User
VOSS	Vertically-variable Ocean Sail System
WASP	Wind-Assisted Ship Propulsion

1 Introduction

Flettner rotors, or rotor sails, are a type of wind propulsion technology for ships which, by using a rotating, electrically-powered column, exploit renewable wind energy using the Magnus effect[1] to provide forward propulsion to a vessel (Searcy, 2017). The devices, producing thrust auxiliary to the main engine, can reduce fuel consumption by between 5 and 20%, according to the International Maritime Organization (IMO) (IMO, 2020).

This thesis aims to describe the latest developments in the Flettner rotor (FR) innovation system and explore human factors in operation to inform stakeholders and produce recommendations for policy and industry. Recent deployment of Flettner rotors (FRs) on a number of commercial ships provides a relatively new opportunity to gain qualitative understanding of FR operation from expert practitioners.

By drawing on innovation systems theory, specifically technological systems and the concepts of structures and dynamics, it is possible to use practitioner knowledge to firstly, map the key organisations and institutions of which the system is currently composed and, secondly, explore the knowledge flow, interaction and interinfluence between them regarding the implementation and operation of FRs.

Then, based on the discipline of human factors, or ergonomics, this thesis draws on practitioner experience, primarily from crew members but also shipping company experts and researchers, to explore FR impacts on vessel operations and the interaction of the technology with crew members.

The project has been undertaken on behalf of SSPA Sweden AB, a maritime research institute and consultancy in Gothenburg, Sweden, as part of a European Commission North Sea inter-regional programme on Wind-Assisted Ship Propulsion (WASP).

1.1 Significance and Policy Context

Maritime shipping was responsible for the emission of 961 million tons of carbon dioxide equivalent (CO_2e) emissions into the world's atmosphere in 2012, representing 3.1% of total anthropogenic greenhouse gas emissions (GHG) emissions and having grown at a rate of 70% between 1990 and 2014, according to the Third IMO GHG Study (Smith et al., 2014). The growth of demand and the, as of yet, slow efforts to decarbonise, set shipping emissions on course to increase 50-250% by 2050, comprising 17% of total anthropogenic CO_2 emissions if left unregulated (Smith et al., 2014). Furthermore, the sector produces large amounts of air pollutants such as Nitrogen Oxides (NO_x), Sulphur Oxide (SO_2) and black carbon (Lack et al., 2015; Smith et al., 2014). Reducing overall emissions is thus a priority for the sector and will contribute to meeting the targets set by the Paris Agreement to keep global warming below 1.5-2°C (UNFCCC, 2015).

The 2008 Kyoto Protocol set the first and, to date, only target in place on the shipping sector: a 50% GHG reduction by 2050, relative to 2008 levels, with responsibility for implementation

[1] The Magnus effect, related to the Bernoulli principle, dictates that airflow around a rotating cylinder or sphere will produce a force perpendicular to the airflow (Searcy, 2017). The force may be familiar to football or tennis players who 'curve' or 'slice' a ball to induce rotation, producing an unpredictable trajectory for the opponent.

falling on the IMO (Smith et al., 2014). In 2011, the IMO adopted the following two energy efficiency policies (Cames, Graichen, Siemons, & Cook, 2015):

- The Energy Efficiency Design Index (EEDI), setting standards for energy efficiency for all vessel new-builds after 2013;
- The Ship Energy Efficiency Management Plan (SEEMP), requiring emissions monitoring and potential efficiency improvement.

However, the impact of the above policies is estimated to be only about a 25% GHG reduction by 2050, meaning further action is required (Rehmatulla, Parker, Smith, & Stulgis, 2017). In response, the 2013 European Union (EU) GHG reduction strategy set out plans for three CO_2 reduction requirements for shipping companies operating in the European Economic Area (EEA), coming into effect between 2018 and 2019 (European Commission, 2020):

- Monitoring of CO_2 emissions, fuel consumption and other parameters for each vessel;
- Formation of a yearly verified emissions report;
- Possession of a compliance document subject to inspection.

Following this, the IMO developed a global fuel consumption reporting requirement for all ships over 5,000 Gross Tonnage (GT)[2] in 2018 and agreed to form the Initial IMO GHG Strategy (European Commission, 2020). However, short-, mid- and long-term energy efficiency measures, research and innovation required to meet the Paris Agreement targets have still yet to be developed (European Commission, 2013).

Existing solutions to increase energy efficiency are offered by technologies such as low-carbon fuels, efficient hull and propeller design, on-board electrolysis, route optimisation and wind energy as a means of propulsion (Bännstrand, 2016; Werner, Li, & Santén, 2020). The development and combination of such technologies offers a solution that not only meets the required targets, but sets sail towards a future of zero-emissions shipping (RINA, 2019a).

In 2019, Resolution 74(5) by China to the Marine Environmental Protection Committee (MEPC) was adopted by the IMO, incorporating wind propulsion into EEDI calculations (IMO, 2019) and in January 2020, by request of Comoros, the IMO adopted Resolution 75(26) to the MEPC, calling for increased consideration of wind propulsion (IMO, 2020). Described as "one of the leading decarbonisation technologies" (p1), wind propulsion technologies offer fuel savings of 5 to 20% already, and potentially more with further development and optimisation (IMO, 2020).

1.2 Background of Wind Propulsion on Ships

Several different technologies exist which can provide forward thrust to a vessel by harnessing wind power (IMO, 2020). While traditional soft sails have been used for millennia in shipping, a group of modern technologies enable large modern vessels to source a considerable proportion of their thrust from renewable wind energy, providing auxiliary propulsion in addition to the main engine and resulting in a reduction in fuel consumption and GHG emissions (IMO, 2020; Rehmatulla et al., 2017; Searcy, 2017).

[2] A standard measurement of ship size used for passenger and RoPax vessels, reflecting overall volume (Bradley, 2017).

Today, a number of technologies exist in various stages of development: Flettner rotors (FRs), soft sails, hard sails, towing kites, suction wings, turbines and hull forms (IMO, 2020). They are different types of devices that provide wind assisted propulsion in new builds or retrofits and can contribute to future designs for fully-wind-propelled vessels (Werner et al., 2020). Such devices offer advantages over many decarbonisation technologies because they cost less, require no additional port infrastructure and can be retrofitted onto much of the world's existing commercial fleet (IMO, 2020; Werner et al., 2020).

Despite having yet to reach commercialisation, market analysts predict rapid growth of the sector in the years ahead (IMO, 2020). A study commissioned by the EU estimated that if wind propulsion technologies reach commercialisation in 2020, the amount of installed devices could reach between 3,700 and 10,700 by 2030 (Nelissen et al., 2016). Furthermore, the UK Government's Clean Maritime Plan predicts that the global wind propulsion market could grow from £300 million per year in the 2020s to about £2 billion per year by 2050 (Department for Transport, 2019). As of 2020, FRs are the most mature wind propulsion technology (IMO, 2020), and among the highest performing (Bentin et al., 2016; Lu & Ringsberg, 2019; Traut et al., 2014).

Figure 1-1 *'The* M/S Viking Grace *berthed at Stockholm's Stadsgården harbour, viewed from the stern'. Source: Author's own work.*

First invented by Anton Flettner in Germany and demonstrated on the vessel *Buckau* in 1924, the FR was highly effective but proved ahead of its time, being outcompeted by conventional engines due to cheap oil prices (Searcy, 2017). Since then, the technology has lay dormant until a recent intersection of unstable oil prices and the development of maritime emissions regulations produced renewed interest and, eventually, uptake (Searcy, 2017). Currently, six commercial vessels operate FRs, with further installations expected later this year (IMO, 2020).

Proven fuel savings have been publicised for a number of operational ships, including 6.1% from two rotors on the roll-on roll-off freight (RoRo) vessel, *MV Estraden*, 8.2% from two rotors on the large tanker, *Maersk Pelican* and up to approximately 20% the small general cargo vessel *Fehn Pollux* (IMO, 2020). Another rotor vessel is shown in Figure *1-1*, the roll-on/roll-off passenger (RoPax) high-speed ferry *M/S Viking Grace,* which has operated a FR since 2018 (Norsepower Oy, 2019).

1.3 Problem Definition

Despite the recent installations, the uptake of FRs remains slow and restricted to a handful of early-mover shipowners (Nelissen et al., 2016; Rojon & Dieperink, 2014). Many authors identify barriers to the growth of wind propulsion technologies in general, such as technical characteristics, a lack of shipowner trust in operational and performance information, uncertainty of business cases and lack of access to funding (Balcombe et al., 2019; Mander, 2017; Nelissen et al., 2016; Rehmatulla et al., 2017). However, no studies exist which attribute these issues to any one technology, justifying an investigation solely into FRs in order to provide a more detailed analysis of the sector.

Furthermore, new automated technological solutions increase the complexity of vessel operations, creating a situation where their effectiveness highly depends on the interconnectivity, collaborative learning and communication between crew members and coordinators onshore (Grech, Horberry, & Koester, 2008; Man, Lundh, & MacKinnon, 2019). Thus, consideration of the human element becomes increasingly important (Da Conceição, Dahlman, & Navarro, 2017) but remains generally overlooked in the maritime industry (Costa, 2018).

Applying a systems thinking approach, the researcher can identify the knowledge capacities requiring mobilisation across different socio-technical levels of operation, namely the departmental (vessel), the organisational and institutional levels (Man et al., 2019). This will enable end-users to inform the design, management and policy decisions that characterise their social and technical environment (Man et al., 2019).

1.4 Objectives and Research Questions

1.4.1 Objective

This thesis aims to paint a holistic picture of the interaction of FRs with the existing Socio-Technical System (STS) of vessel operations at different layers of a Multi-Level Perspective (MLP). Two theoretical frameworks are applied: Technological Innovation Systems (TIS) theory and human factors. The first is used to map the current structural components active in FR innovation and the dynamics of interaction between them, comparing it to existing literature. Secondly, human factors, or ergonomics, are used to describe FR interaction with onboard vessel operations, based on user experience.

The findings are used to prescribe to provide solutions, in the form of recommendations to specific actor groups, to develop the innovation system and improve FR integration into the maritime socio-technical system.

1.4.2 Research questions

This gives rise to three research questions, the first two of which are descriptive and the final of which is prescriptive, providing recommendations based on findings. Mapping the innovation system (Research Question 1), allows for an exploration of the current knowledge activities and their interaction and development over recent years. Research Questions 2 and 3 analyse the interaction of FRs with existing vessel operations and how they influence each other, with the latter prescribing recommendations for improvements.

The research questions are as follows:

1. What is the current state of the FR innovation system and how has this evolved?
2. What are the disruptions by FRs to the socio-technical system of vessel operations, according to operational experience?
3. What adjustments to the socio-technical system should be made to optimise FR operation, performance and uptake?

1.5 Scope and Delimitation

FRs are the most mature wind propulsion technology (IMO, 2020) and thus offer a great opportunity for obtaining data concerning the innovation system and operational experience. There are six crews currently operating the devices on commercial vessels and a number of competing providers of the technology (IMO, 2020; IWSA, 2020a).

The topic of this thesis is commonly referred by using the term “Flettner rotor” in academic literature, while in industry the devices are often called a “rotor sails” or even simply “rotors” (IMO, 2020; IWSA, 2020b). These are synonyms for the same technology and can be used interchangeably.

FR technology has been studied applying innovation systems theory by a number of authors, albeit in the context of general wind propulsion technology, providing an opportunity to compare this thesis’ findings with literature and explore the evolution of the sector over time. Any actors involved in the innovation system are deemed relevant to the research.

It was decided not to impose any geographic limitations upon the research because of the relatively small number of operational vessels and technology providers. That being said, it is unlikely that the resulting network map is exhaustive, and mapping is subjectively influenced by the data collection process. The system components and network should therefore be treated as an approximation, without clearly defined boundaries.

Human factors research functions by analysing a human user’s perspective of, and interaction with, technology. One appropriate data collection method requires the researcher to physically observe operations on board a vessel. Due to resource constraints, it was unfeasible to conduct observation aboard all six FR vessels but the findings from one vessel are nonetheless a valuable and representative case of human factor interaction with FRs.

1.6 Ethical Considerations

Throughout the thesis process the core ethical principles of research have been adhered to. The list below contains the ethical considerations deemed relevant to ensuring good research practice, based on the work of Blaikie & Priest (2019).

- This thesis was undertaken on behalf of SSPA Sweden AB, the author receiving funding from the European Regional Development Fund (ERDF) for contribution to a deliverable of the WASP Interreg program, as well as reimbursements for travel expenses incurred. Research independence was consistently protected from influence of external interests during the mentorship process.
- It was ensured that all relevant results from the empirical data collection were honestly and faithfully reported in this thesis to the best of the author's ability. No contrary or inconvenient data was omitted from the findings and research limitations are carefully reflected upon and presented in Section 5.4.
- Interaction with research participants was undertaken respecting the principle of Informed Consent, including protection of respondent confidentiality. Before each interview began, a statement of confidentiality was read to the respondent to clarify that the notes or transcript of the interview would be sent to them before data analysis began, so that they could make any changes and remove any erroneous or sensitive information. The original transcripts were stored in a password-protected online drive and deleted if replaced by the interviewee. If audio recording or photo permission was requested, this was asked in advance and evidence of consent was documented. It was also explicitly stated before each interview that participation was voluntary and respondents were free to leave any question unanswered or leave the interview at any point.
- During direct observation of crew and operations on board the *M/S Viking Grace*, it was ensured that participants were not performing unusual tasks for the sake of the data collection that may cause unnecessary risk to them or myself. When observing heavy machinery, such as Flettner rotors, all onboard safety guidelines were followed and in no situation were crew distracted or interrupted from their duties.

This research design has been reviewed against the criteria for research requiring an ethics board review at Lund University and has been found to not require a statement from the ethics committee.

1.7 Audience

The intended audience for this thesis comprises of shipping industry stakeholders and policy makers. Stakeholders include FR technology providers, shipowners operating FRs and other shipowners seeking information and advice about the technology. Policy makers are targeted at a number of levels; from regulators at the IMO and EU and national legislators to decision-makers in port authorities and local municipalities. Furthermore, this document is intended to inform organisations lobbying for policy changes, such as environmental Non-Governmental Organisations (NGOs) and maritime associations.

Additionally, as a Master's thesis, this paper is also aimed at an academic audience of researchers of innovation systems and human factors as well as anybody with an interest in maritime decarbonisation technology.

1.8 Disposition

Chapter 1 contains an outline of the decarbonisation problem facing the maritime sector, the policies so far put forward to address this and an explanation of wind propulsion technology including specific detail on FRs. Then the objectives research questions of this thesis are presented and the scope clarified. Chapter 2 is a review of academic research concerning FR innovation and operation and a detailed explanation of the theoretical frameworks employed in this thesis. The research design and methods for data collection and analysis are explained in Chapter 3.

Chapter 4 is the results section and is divided in two. The first part consists of describing the current situation of FR innovation by mapping the actors and processes at work in the sector. The second part of the results documents the findings from operational experience of FRs, including technical and human factor insights on FR operation and performance.

The main findings are discussed in comparison with literature in Chapter 5. Furthermore, the theory, methods and findings are reflected upon, including an evaluation of the methodological limitations to this study.

Chapter 6 provides clear and succinct recommendations to influential actors, suggesting possible improvements to FR innovation, operation and performance. Furthermore, the main findings of this thesis are summarised and areas for further research explored.

2 Literature Review

2.1 Flettner Rotors

FRs are an elusive subject in academic literature; a quick search using the academic research database ScienceDirect will reveal only nine research articles containing the term "Flettner rotor" or "rotor sail" in their abstract, title or keywords (Elsevier B.V., 2020). This review begins by exploring existing literature on the fuel savings and GHG emissions reduction performance of FRs, then operational impacts of FRs on ship operations before finally investigating literature concerning policies to encourage the uptake of FRs and wind propulsion technologies in general.

2.1.1 Impact on ship operations

Operational impacts of FRs on ship stability and navigation are explored somewhat in literature. Tillig et al. (2020) recorded that in downwind and headwind scenarios, heeling may become too large to be counteracted by the rudder angle and drift forces resulting from FR drag may outweigh thrust from the device(s). In such cases, the FR(s) are 'reefed', meaning their rotation speed (rpm) is lowered, reducing their thrust (Tillig et al., 2020). Bordogna et al. (2020) performed wind tunnel experiments to assess the effect of the spacing of two FRs on a ship's deck on heeling; they found that FRs spaced further apart will produce less heeling. In a contradictory study, Copuroglu & Pesman (2018) performed fluid dynamics calculations which showed that FRs have no influence on heeling.

Rehmatulla, Parker, Smith, & Stulgis (2017) and Mander (2017) mobilised qualitative wind propulsion operational experience from expert practitioners such as crew members or technical personnel. They identified some impacts on ship operations and possible limitations to technology expansion as being heeling, obstruction of bridge visibility, cargo handling, waterway inaccessibility due to increased air draught and crew safety and training.

The qualitative studies by Mander (2017) and Rehmatulla et al. (2017) analysed wind propulsion in general and did not attribute these impacts to any one type of technology. Furthermore, the descriptions of impacts lack any more detail than is mentioned above. An investigation into operational impacts specifically due to FRs allows for a more detailed description and direct attribution to a technology, as well as a resolving of the contradictory results of heeling impact visible when comparing the studies by Bordogna et al. (2020) and Copuroglu & Pesman (2018).

2.1.2 Performance

FR performance is determined by a number of related parameters: fuel consumption reduction, GHG emissions reductions, air pollutant emissions reductions and monetary fuel cost savings (Talluri, Nalianda, & Giuliani, 2018). Authors emphasise different parameters depending on the perspective of their studies (Talluri et al., 2018) but each is proportional to the other, the central parameter being fuel consumption reduction (Lu & Ringsberg, 2019).

Lu & Ringsberg (2019) simulated FR fuel saving performance on an Aframax oil tanker, concluding that savings were between 5.6 and 8.6%. Comparing two models of a bulk carrier under 50,000 deadweight tonnage (dwt)[3] and the larger Aframax oil tanker on two transatlantic

[3] A standard measurement of cargo capacity used for dry cargo carriers, tankers, Ro-Ro, general cargo and container ships, reflecting the difference in displacement when fully loaded to unloaded (Hasan, 2011).

routes, the authors found that FR performance is better on the smaller ship and that performance is enhanced when the FR is located at the fore of the vessel, as opposed to the midship. Fuel savings depend on ship type, route of voyage and vessel speed, but not necessarily FR size or rotation speed (Lu & Ringsberg, 2019).

Talluri, Nalianda, & Giuliani (2018) explored the potential monetary savings and GHG emissions reductions of FRs, concluding that fuel consumption and environmental emissions can be reduced by up to 20%. Comer, Chen, Stolz, & Rutherford (2019) modelled fuel savings for five real-world ships with rotor sails using global traffic data and meteorological data, finding that FRs reduced fuel consumption by up to 12%.

Tillig, Ringsberg, Psaraftis, & Zis (2020) applied a ship energy system model to simulate between 1 and 6 FRs installed on a medium range tanker, finding fuel savings of 71 tonnes per year, or 12%, of Heavy Fuel Oil (HFO), corresponding to reducing 221 tonnes of CO_2 per year. Fuel savings can be achieved even on routes with unfavourable average wind conditions (Tillig et al., 2020).

FR performance in different ship stability conditions was explored by Copuroglu & Pesman (2018) who found that FR thrust decreases with increased vessel heeling. Bordogna et al. (2019) performed experiments to find that the power consumption of an FR is not affected by wind turbulence while Bordogna et al. (2020) found through experimentation that increased spacing between two FRs increases their performance.

Using numerical models, Bentin et al. (2016) and Traut et al. (2014) studied the effect of route optimisation on FR fuel savings performance, compared to towing kites and soft sails. They found that FRs produce higher average fuel savings that kites, as did Lu & Ringsberg (2019), and that small modifications to a vessel's route increases fuel savings significantly due to wind and sea current influence. Bentin et al. (2016) concluded that route optimisation is an important opportunity for increasing fuel savings from wind propulsion technologies.

There is a variety of literature exploring factors influencing FR fuel saving performance, such as vessel routing, heeling, wind flow conditions and deck arrangement of FRs. However, the factors investigated are entirely technical while human factors have so far been unexplored.

2.1.3 Decarbonisation policy

Rojon & Dieperink (2014) took a technological perspective of innovation systems theory, analysing the structural components and the dynamic changes in the system, represented by seven functions, for three wind propulsion technologies: towing kites, sails (hard and soft) and FRs. They formulated a set of drivers and barriers controlling wind propulsion technology uptake, concluding that the barriers outweigh the drivers and development of the innovation system is hindered by a lack of access to financial resources, lack of policy incentives, lack of cooperation between actor groups and conservative attitudes in the shipping industry. They recommended that policy solutions should focus on increasing collaboration and knowledge sharing between actors and mobilising resources.

Rehmatulla et al. (2017), Mander (2017) and Balcombe et al. (2019) offered more up-to-date analyses of wind propulsion innovation and barriers to transition. Rehmatulla et al. (2017) concluded, by means of a content analysis, that shipowners are discouraged by risks and unreliability due to unproven technology and distrust of fuel saving claims. They revealed a market failure of split incentives and argued for creative policy solutions to overcome this and increase access to funding. Mander (2017) explored wind propulsion innovation, explaining how the wind propulsion niche has evolved to produce collaborative initiatives for knowledge sharing such as the EU-funded SAIL project and the International Windship Association (IWSA). However, she found that lack of access to funding continued to be a barrier and argued that hybridisation with incumbent propulsion and route optimisation may be key developments for the future. Balcombe et al. (2019) and Nelissen et al. (2016) found that wind propulsion technologies in general are hindered by shipowner unfamiliarity, risk-averse attitudes and high uncertainty of cost efficiency.

Searcy (2017) analysed the potential of implementing FRs on commercial vessels on Pacific-island countries. The intersection of a strong seafaring tradition, uneconomical shipping routes due to unaffordable oil prices and the demonstrated success of FRs have the potential to provide government savings to Fiji of between US$348,042 and $522,063 over twenty years and emissions reductions of between 2,931 and 4,396 tonnes of CO_2.

Karslen, Papachristos, & Rehmatulla (2019) adopted a transitions perspective, modelling the potential diffusion of FRs from 2020 to 2050 in time-charter dry bulk vessels globally. In this study, an agent-based model for innovation niches by Lopolito, Morone, & Taylor (2013) was modified to formulate twelve processes of innovation dynamics simulating actor interaction (Karslen et al., 2019). The research demonstrated that learning from full-scale applications of fledgling technologies is a key part of innovation diffusion in niche environments and recommends that the introduction of carbon pricing policy should coincide with demonstration project policies for maximum effect (Karslen et al., 2019).

2.2 Theoretical Frameworks

This thesis makes use of two theoretical frameworks for analysing new technology from an STS perspective: TIS and human factors, otherwise known as ergonomics. Each theory is explained, brought into a maritime context and applied to FRs, in turn, to frame the findings.

2.2.1 Socio-technical systems and the multi-level perspective

A system is defined as "a set of interacting and interdependent components that form an integrated whole" by Dul et al. (2012). A STS perspective seeks to understand the interaction between people with system components in the context of the larger environment (Carayon, 2006). Recognising and defining problems in systems requires the delimitation of boundaries in order to process their complexity (Loorbach, 2007). One common approach is the application of the MLP (Carayon, 2006; Costa, 2018; Dul et al., 2012; Kleiner, 2006; Loorbach, 2007; Zanetti, 2013), which conceptualises the STS into three distinct levels: the micro, meso and macro (Geels, 2002). The levels represent different scales of society; the micro is the actions and interaction of individuals, the meso is the interaction and structure of multiple individuals and the macro is the framework encompassing society in general (Dul et al., 2012; Geels, 2002; Loorbach, 2007).

Exactly how the constituents of the MLP levels are defined can vary depending on the task of the research and multiple points of view can complement each other in interdisciplinary research (Costa, 2018). The following theoretical frameworks are presented, offering diverse and complimentary points of view when exploring new technology in an STS context.

2.2.2 The Flettner rotor innovation system

Innovation, according to Loorbach (2007), is the evolution and development of new technologies as well as the formation and tolerance of new ideas and concepts. The social and technical aspects of this definition are mutually dependent and each fundamental to the creation of innovation and thus, is a socio-technical process (Loorbach, 2007).

Innovation systems theory, as described by Carlsson & Stankiewicz (1991), Edquist & Johnson (1997) and Hekkert et al. (2007), is a framework for analysing the evolution and development of technology in complex STS by conceptualising knowledge flow between system components and levels as the core, defining variable. TIS (also known as Technology Systems or Technology-Specific Innovation System) theory looks at innovation systems from the perspective of one technology, as opposed to sector- or nation-specific perspectives (Hekkert et al., 2007). This approach is the most dynamic because it cuts across sectoral and national boundaries, reflecting the reality of modern innovation systems (Hekkert et al., 2007). For this thesis, a TIS perspective is adopted for analysis of FRs, referred to hereafter as the Flettner Rotor Innovation System (FRIS).

TIS is centrally underpinned by the MLP and models the IS into three micro, meso and macro levels: ‘niches’, ‘regimes’ and ‘the landscape’ (Geels, 2002). The niche forms a space where innovation can occur due to local or individual development and interaction, and where new technologies can iterate and evolve in an artificially protected environment (Hekkert et al., 2007). The niche exists because the technology is able to fill a certain market function that the incumbent technology cannot, or, it is protected and supported by certain interests (Geels, 2002). The regime is the TIS of the incumbent, ‘normal’ or ‘mainstream’ technology, which is self-sufficient and stable (Geels, 2002). A successful innovation is one that is able to break free from the niche, subvert the regime and, rendering it obsolete, replace it as the incumbent technology (Hekkert et al., 2007). Finally, the landscape defines the possible actions of organisations in the niche and regime, consisting of political, regulatory or legal bodies (Geels, 2002).

2.2.2.1 Organisations and institutions

Carlsson & Stankiewicz (1991) and Edquist & Johnson (1997) conceptualise two structures in a TIS: organisations and institutions. Organisations occupy the niche and regime levels which institutions make up the landscape.

Organisations are formal structures created to enact specific purposes, exploiting opportunities enabled by the landscape (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997). Institutions are the normative human-made structures forming the landscape around organisational activity to stabilise and shape interactions (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997). They can be both formal and informal; formal institutions are written into legislation, such as laws and regulations, while informal institutions are implicit and behavioural, such as traditions, practices and expectations (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997). While institutions envelop and constrain the activities and potential of organisations, they can also be influenced and changed by them (Edquist & Johnson, 1997).

Here, a distinction must be made for the purpose of this thesis between the types of bodies that can be considered organisations and those that form institutions. Economic bodies, or firms, and social bodies such as universities and research institutions are all considered organisations. On the other hand, the institutional landscape is comprised some tangible ‘organisations’, such as regulatory bodies and national or supra-national legislators, that are not included in this definition of organisations and instead make up the landscape of the TIS.

2.2.2.2 Networks

The flow of knowledge or competence within and between organisations and institutions is the defining variable of a TIS (Carlsson & Stankiewicz, 1991). The components form connections and communicate with one another, and the overview of different connections is called a network (Carlsson & Stankiewicz, 1991).

The levels of knowledge required to produce innovation in a TIS necessitate the formation of connections between organisations (Carlsson & Stankiewicz, 1991). Networks arise when organisations form connections for mutually-advantageous knowledge sharing (Carlsson & Stankiewicz, 1991). Their essential purpose is facilitating information transfer, but they can also consist of material flows (Carlsson & Stankiewicz, 1991). The network concept of this thesis comprises of two types of industrial relationships: user-supplier relations and knowledge networks (Carlsson & Stankiewicz, 1991).

Using the above definition of organisations, it is possible to map a TIS network, taking into account both formal relationships, such as user-supplier relations, and informal communications, such as associations and affiliations between organisations. It is acknowledged that network boundaries are imprecise and can never truly defined (Carlsson & Stankiewicz, 1991). Instead the analysis will serve as an approximation of the network's size and ability to transfer information between organisations.

2.2.2.3 Dynamics

System dynamics are activities which change the interaction of structural components, such as new entrants and changes in legislation (Hekkert et al., 2007; Johnson, 2001; Liu & White, 2001). For TIS, it is possible to identify these activities from empirical research due to the relatively small amount of structures (organisations and institutions), when compared to national and sectoral innovation systems (Hekkert et al., 2007). The relevance of dynamics is determined by whether they impact (positively or negatively) the key TIS goals of creating, developing, applying and transferring technical knowledge (Hekkert et al., 2007). The dynamics are by (Hekkert et al., 2007; Rojon & Dieperink, 2014).

Hekkert et al. (2007) propose seven system functions (F1 to F7) to structure, or 'map', empirical findings concerning TIS dynamics. These seven 'functions of innovations' or 'system functions' offer policy-makers an understanding of crucial activities and patterns in a TIS and is a useful tool to guide and support policy makers (Hekkert et al., 2007) and generate recommendations (Smits & Kuhlmann, 2004).

Function 1 (F1), entrepreneurial activities, analyses the activities relative to 'early movers' in the TIS, or those organisations that are at the forefront of innovation (Hekkert et al., 2007). Activities important for this function are who is adopting the new technology and why, linkages with other organisations and competitors. Analysis of entrepreneurs can be undertaken by mapping the new entrants into the TIS and the uptake of the new technology by incumbent organisations (Hekkert et al., 2007).

F2 concerns knowledge creation in two forms: 'learning by searching' and 'learning by doing' (Hekkert et al., 2007). Mapping of this function is approached by documenting Research and Development (R&D) projects relevant to FRs, assessing the technological variety in the TIS by describing the diversity of patented FR types and counting the number of operational reference projects which enable learning by doing.

Knowledge diffusion through networks (F3) is the sharing of ideas between groups of actors and is key to enabling and developing innovation (Hekkert et al., 2007). Using an approximation of the IS organisational network structure for guidance, this function is an elaboration of connections between organisations and mediums for 'learning by interacting', achieved through mapping the formal and informal communication channels and partnerships existing in the network (Hekkert et al., 2007).

F4, the guidance of the search, concerns activities that increase awareness and expectations of TUs (Hekkert et al., 2007). Mapping the function is performed in two parts: firstly, any specific policy targets influencing R&D and uptake are identified and, secondly, the operational and performance expectations of TUs and PTUs are described (Hekkert et al., 2007).

Market formation (F5) is the process by which new technologies can fill a niche, either by offering a specific and unique market service or by providing a competitive advantage due to favourable regulations or taxes (Hekkert et al., 2007). The niche forms an important environment where the technology can develop, protected from the incumbent regime. The markets, regulations or tax schemes are mapped in this function (Hekkert et al., 2007).

Resource mobilisation (F6) is an indicator of access to resources, financial or other, for enabling activity in the TIS and the difficulty in accessing those resources, especially for learning by searching or learning by doing (Hekkert et al., 2007).

Finally, F7, creation of legitimacy, concerns the ability of the niche technology to form coordinated interest groups to alter the landscape through lobbying, enabling either the merging with, or overthrowing of, the incumbent regime (Hekkert et al., 2007). Mapping of the function is performed by identifying any groups able to lobby for the interests of the new technology and any resistance by incumbent interest groups (Hekkert et al., 2007).

The seven functions explained above interact and influence each other positively or negatively to fulfil or impede each other and determine the development of the TIS (Hekkert et al., 2007). It is expected that the mapping the functions produces a non-linear model of function interaction, providing insight into the strength of the system and the direction of change (Hekkert et al., 2007).

2.2.3 Human factors

Human factors, or ergonomics, is "a scientific discipline concerned with the understanding of the interactions among humans and other elements of a system", according to the International Ergonomics Association (IEA) (IEA, 2020). Its aim is to produce better outcomes for human well-being and system performance by optimising the design and the continuous improvement of systems (Carayon, 2006; IEA, 2020). Human factors research intrinsically follows a STS perspective, being an analysis of the linkages between the human (social) element and the system (technical) (Carayon, 2006; Costa, 2018) and always maintaining a human-centric viewpoint (Dul et al., 2012).

As STS and their interactions become more complex, human factors become increasingly valuable when paired with other disciplines (Carayon, 2006). Human factors are, by definition a multi-disciplinary and holistic field (IEA, 2020) and can produce insight and knowledge of system processes when integrated into other disciplines, while consistently remaining user-oriented (Carayon, 2006). Effective and appropriate use of human factors in STS contexts produces fulfilment of a technology's intended purpose (Vicente, 2007) and can, itself, contribute to innovation (Carayon, 2006).

Conceptualisation of human-STS interaction is achieved at different scales using the MLP (Carayon, 2006; Costa, 2018; Dul et al., 2012). The micro level consists of individual tasks and utilisation of tools, the meso level comprises the human's role in an organisation or technical process and at the macro level, the human is placed in the context of the wider societal context of networks, political entities and culture (Dul et al., 2012).

2.2.3.1 Human factors in the maritime domain

The commercial shipping industry is a complex STS (Costa, 2018; Da Conceição et al., 2017; Grech et al., 2008) where humans play a critical role in maintaining the functioning of the system as ship crews (Anastasiou, 2017; Grech et al., 2008; Latarche, 2013). The introduction of new technology, however advanced and seemingly immune to human misuse, must therefore be accompanied with an analysis of human factors to uncover and correct any issues impacting human well-being and STS performance (Grech et al., 2008).

This is relevant to technologies for reducing GHG emissions because the crew's navigation and interaction with propulsion systems directly influence a vessel's fuel consumption (Man et al., 2019). FRs, as auxiliary propulsion systems with evidence of influence on navigation (Bordogna et al., 2020; Tillig et al., 2020), should therefore be analysed using human factors to ensure human well-being is not harmed and to improve their function as a technology for reducing GHG emissions.

Applying the human factors MLP to the maritime domain, the micro level concerns the interaction of humans and technology in a department, or vessel (Man et al., 2019), which can be conceptualised by key crew work tasks and the user's interface (Grech et al., 2008). The five maritime work tasks are a categorisation of crew operations into the following functions: navigation, propulsion, cargo/passenger handling, deck maintenance and ship management (Grech et al., 2008). The meso level is the organisation, placing the crew in the context of employees at a shipping company (Man et al., 2019), where their well-being and performance is directly influenced by crew management, consisting of instruction and training, communication with the employer and expectations management (Anastasiou, 2017). At the macro level, the crew is shaped by informal norms and culture, as well as formal decisions taken by institutions, such as IMO regulations (Grech et al., 2008).

Man et al. (2019) explore the human factors of a vessel crew's interaction with a fuel consumption monitor, a technology for improving energy efficiency. They found that the design of the user interface was important in ensuring correct usage and providing instruction of fuel consumption reduction. Furthermore, it was argued that communication and collaboration between different crew members and information sharing between crew and onshore management is increasingly important for new technologies aiming to improve fuel efficiency (Man et al., 2019).

3 Research Design and Methods

3.1 Qualitative Research Approach

The collection of empirical data was followed a qualitative approach. This suited the theoretical frameworks of TIS and human factors because their primary key concerns, the transfer of knowledge and human well-being respectively, are inevitably linked to the immeasurable subjective human experience. Qualitative data collection allows for a richness of understanding of the socio-technical processes inherent in TIS theory and human factors (Edquist & Johnson, 1997; Hekkert et al., 2007).

While a qualitative approach can be criticised for being subjective and non-generalisable (Blaikie & Priest, 2019), the objective of this research is to produce recommendations and solutions across a wide spectrum of cases, identifying the variables that define which solutions are appropriate and where.

3.2 Data Collection Methods

Three qualitative methods were used and data triangulated answer the research questions: semi-structured interviews, document analysis and direct observation. Mapping the current state of the FRIS (Research Question 1) was conducted using semi-structured interviews and document analysis, while the data collection for exploring FR operational experience (Research Questions 2 and 3) consisted of semi-structured interviews of crew members and direct observation on board the vessel *M/S Viking Grace*. Secondary operational data was also obtained in the semi-structured interviews of expert practitioners.

3.2.1 Document analysis

The early framing of the research topic and a preliminary outlining of the FRIS structure was conducted using a document analysis method, following the so-called snowballing technique. Document analysis is the collection and analysis of non-academic literature (Sovacool, Axsen, & Sorrell, 2018). Information was collected from documents such as industry reports, presentations, conference proceedings, magazine articles and pertinent web pages.

This method was relevant to TIS research because produces insight into the information, perspectives and interaction between different actors (Sovacool et al., 2018) and because, in the case of the FRIS, there is a lack of up-to-date academic literature. Snowballing was important for innovation systems research because it enables the identification of natural social networks (Blaikie & Priest, 2019).

The method was used early on, enabling identification of relevant organisations to approach for interviewing. It continued to prove important throughout the thesis, with new resources being discovered using documents provided by interview respondents.

3.2.2 Semi-structured interviews

Semi-structured interviews were used to gain evidence of a respondent's experience of an activity or process (Sovacool et al., 2018) and for assessing usability of technology based on operational experience (Costa, 2018; Kirwan & Ainsworth, 1992). Thus, expert practitioner knowledge was collected through interviews inform both the FRIS and human factors theoretical frameworks. Respondents were firstly identified using document analysis and later through snowballing of interviewees' suggested contacts.

Following the guidelines of Adams (2015), interviews began with open and general questions, then lead to follow-up questions. This produced a balance between the interviewee offering their perspective of important subjects, while enabling them to be steered towards topics relevant to the thesis, as decided based on the theoretical frameworks. Follow-up questions were used to clarify specific information, such as where information was sourced and quantification of certain parameters, enriching the findings from general questions and delving further into detail when deemed necessary.

Before each interview, a plan of general and follow-up questions was prepared (see Appendix). The formulation of questions was open, but follow-up questions were based on theoretical literature. For example, the five maritime tasks of Grech et al. (2008) provided a straightforward conceptualisation of the different areas of work on board that might be affected by the operation of a FR system. When formulating interview questions, an open question on FR impacts on work on board was asked, before follow-up questions shaped by the five maritime tasks to explore and prompt any areas of operation not yet mentioned.

The semi-structured nature of this data collection ensured that the interview plan was not rigidly obeyed, allowing for it to be tailored, ad-hoc, to the interviewee's particular expertise and knowledge. After each interview, the plan was reviewed and improved iteratively based on the experience of the previous interview, incorporating interviewee feedback.

Interviews were conducted either in-person or remotely. In-person interviews or remote video calls were preferred but, if such interviews were not possible to arrange, phone calls were preferred and, failing that, email correspondence was possible.

Crew interviews were conducted in conjunction with direct observation on board the *M/S Viking Grace*. Depending on the availability of the crew, interviews were performed during their work activities (Pilots and First Engineer) or in a private room while they were off-duty (Safety Officer, Master and Chief Engineer).

Respondents were found using document analysis while outlining the structure of organisations in the FRIS, as explain in Section 3.2.115. As the interviews began, further respondents were identified using the snowballing technique, based on respondent contacts. The respondents comprised of sixteen expert practitioners, including interviews with five crew members of the *M/S Viking Grace* while on board.

The expert practitioners interviewed were employees of organisations that were categorised into the following three groups: technology providers (TPs), technology users (TUs) and potential technology users (PTUs):

- TPs are entrepreneurial companies that design and produce FRs, suppling them to TUs. Practitioners interviewed include senior management staff and one researcher.
- TUs are shipowners operating FR(s) on at least one vessel. Practitioners include senior management staff and crew members.
- PTUs are shipowners who are or were interested in installing a FR or are awaiting installation of a FR. Practitioners are senior management staff.

These three categories (TP, TU and PTU) were used to establish a labelling system that is used throughout the thesis in in-text citations. The label is given to each organisation, based on its category and an assigned number, as shown in Table 3-1. Some interviewees were from the same organisations and are represented by a single label in citations. The specific organisations and others are described in detail when mapping the FRIS in Section 4.1.1.1.

Table 3-1 'Interview respondents and their citation labels'

Organisation type	Respondent role	Organisation	Citation label
Technology Provider	Chief Executive Officer	Norsepower	TP-1
	Chief Operations Officer	Anemoi Marine Technologies Ltd (Anemoi)	TP-2
	Professor of Ship Operation and Simulation	Emden-Leer University	TP-3
	Company spokesperson	Enercon	TP-4
Technology User	Master	Viking Line (interviews were part of a usability assessment on board the *Viking Grace*)	TU-1
	Chief Safety Officer & Pilot		
	Pilot and Co-pilot		
	Chief Engineer		
	First Engineer		
	Chief Executive Officer	Fehn Ship Management	TU-2
	Senior Project Manager	Maersk Tankers	TU-3
Potential Technology User	Manager of Special Projects	Scandlines	PTU-1
	Naval Architect		
	Technical Manager	Donsötank	PTU-2
	Newbuilding Project Manager	Stena Teknik (part of Stena Group)	PTU-3

TPs and TUs were approached for primary data concerning operational experience of FRs. The two types of organisations exist in a relationship of developers and adopters and it was thus important to access knowledge from each to avoid potential bias such as positive supplier bias, negative customer bias and to generally increase diversity of opinions and perspectives.

The third organisational type of respondents, PTUs, was identified to add the perspective of organisations who have yet to install FRs. PTUs were approached based on other respondent knowledge of shipowners that have explored and/or expressed interest in deploying FRs on their vessels in the near future.

When interviewing crew members, the navigation and engine crew were the most relevant because of FRs being propulsion devices and technology to reduce fuel consumption (Man et al., 2019). The senior navigation, or bridge, crew generally consists of the Master, or Captain, the First Officer and, in some cases, Pilots (experts in navigating certain routes, such as port approaches and archipelagos), while the senior engine crew consists of the Chief Engineer and First Engineer (Latarche, 2013).

3.2.3 Direct observation

The method of direct observation is useful for witnessing conditions and actions in the workplace in a non-intrusive manner (Sovacool et al., 2018) It differs from participant observation in its emphasis on minimising intrusion (Kirwan & Ainsworth, 1992) and in its aim to collect inductive and exploratory, rather than interpretive, data (Sovacool et al., 2018).

Direct observation was carried out during an arranged visit on board the *M/S Viking Grace*, a 2,800-passenger RoPax ferry operated by Viking Line which sails a regular route between

Stockholm and Turku (Viking Line, 2018). Since 2018, the ship has been is fitted with one FR, located at the top deck, at the midship.

In the context of human factors, the method enables identification of technological usability (Costa, 2018; Kirwan & Ainsworth, 1992) and the influence of new technology on crew work tasks affected on the ship (Grech et al., 2008). In this instance, it consisted of physical observation, image and video recording and note taking. Observation on board the *M/S Viking Grace* was carried out at three locations relevant to FR operation, as identified by the crew: Deck 13 (the top deck), the engine control room and the bridge.

3.2.4 Usability assessment

A usability assessment was conducted onboard the *M/S Viking Grace*, consisting of direct observation and semi-structured interviews. This method is fundamental in diagnosing human factor problems and formulating solutions (Costa, 2018). Secondary usability data was obtained from non-user interviewees, such as shipowners and TPs. While these actors generally did not have experience of directly using the technology, they nonetheless offered knowledge of its operation through communication with crews.

The usability assessment is akin to a case study, in that it consists of deep and exploratory data collection of a specific context using multiple data collection methods (Sovacool et al., 2018). This method provided, firstly, indication of usability issues that could be triangulated with primary user data from crew member interviews and observation. Secondly, it shed light on the organisational, or meso, level of human factors; in other words, the relationship between crew and shipowner or TP could be explored by comparing the experience of the new technology from each perspective.

The current FR stage of development offers the best opportunity to analyse human factors because the technology is built, ready, tested and functioning (Kirwan & Ainsworth, 1992). This provides an ideal context in which to study issues related to skills and knowledge acquisition and the ability of system users to adequately fulfil the tasks required of them (Kirwan & Ainsworth, 1992).

3.3 Data Analysis

Analysis began simultaneously with data collection, with themes becoming increasingly clear throughout the process. These themes for data categorisation and presentation were not built from the ground-up, but drew on the theoretical frameworks gained from literature, more so in analysing TIS than human factors. After an initial conceptualisation of data into themes, the data was reanalysed in text form using Nvivo software, making use of the ‘Nodes’ function to iteratively pursue emerging themes.

Analysis of TIS data drew on the analytical categories of structure and dynamics, provided by Hekkert et al. (2007), and analysis of human factors applied the maritime work task and user interface categorisations identified by Grech et al. (2008). However, these categories were constantly malleable and formed from matching and comparing data from multiple sources with the theoretical frameworks to iteratively redirect and reorient the outcome of the study.

4 Results

This section describes the results from the empirical data collection and is divided between the mapping of the FRIS and findings from operational FR experience. Throughout the results and afterwards, citations of interview data employ the labelling system established in Table 3-1 in Section 3.2.2. Other literature cited in this section is the result of the document analysis data collection method explained in Section 3.2.1.

4.1 Mapping the Flettner Rotor Innovation System

4.1.1 Structure

4.1.1.1 Network and Organisations

A representation of the organisational network, shown in Figure 4-1, is provided as a visual guide to the organisations and connections between them that make up the FRIS, as identified during data collection. The organisations are divided into five groups: Technology Providers (TPs), Technology Users (TUs), Potential Technology Users (PTUs), research institutes and international associations. The first three are based on the respondent categories defined in Section 3.2.2, while research institutes are universities and research consultancies that contribute to FR R&D and international associations are formal partnerships between organisations for networking and collaboration. Institutional actors, such as classification societies and municipal or governmental bodies, are not included in the network.

Figure 4-1 is intended to be used by the reader as a guide to the FRIS organisations and the relationships between them that are referenced throughout this thesis. Furthermore, descriptions of the organisations identified in the network are provided in Table 4-1 to Table 4-5, divided by organisational group.

As organisational groups, TUs and TPs are objectively defined by their activities, whereas PTUs are a result of snowballing of shipowner knowledge. The definition of PTU is therefore subjective, dependent on whether their interest in installing FRs is known to the researcher or whether information concerning an upcoming installation is publicly available. Theoretically, every shipowner on the planet not already operating FRs could be categorised as a PTU but, for the sake of approximately mapping the organisational network, only those mentioned by respondents have been included. Similarly, research institutes and international associations were identified based on snowballing and the lists in Table 4-3 to Table 4-5, especially of research institutes, should by no means be considered exhaustive.

The PTU organisational group contains shipowners who are, or were formerly, interested in installing a FR or are awaiting installation of a FR. A column specifying the PTU's development stage is included in Table 4-3 to clarify each shipowner's relation with FRs.

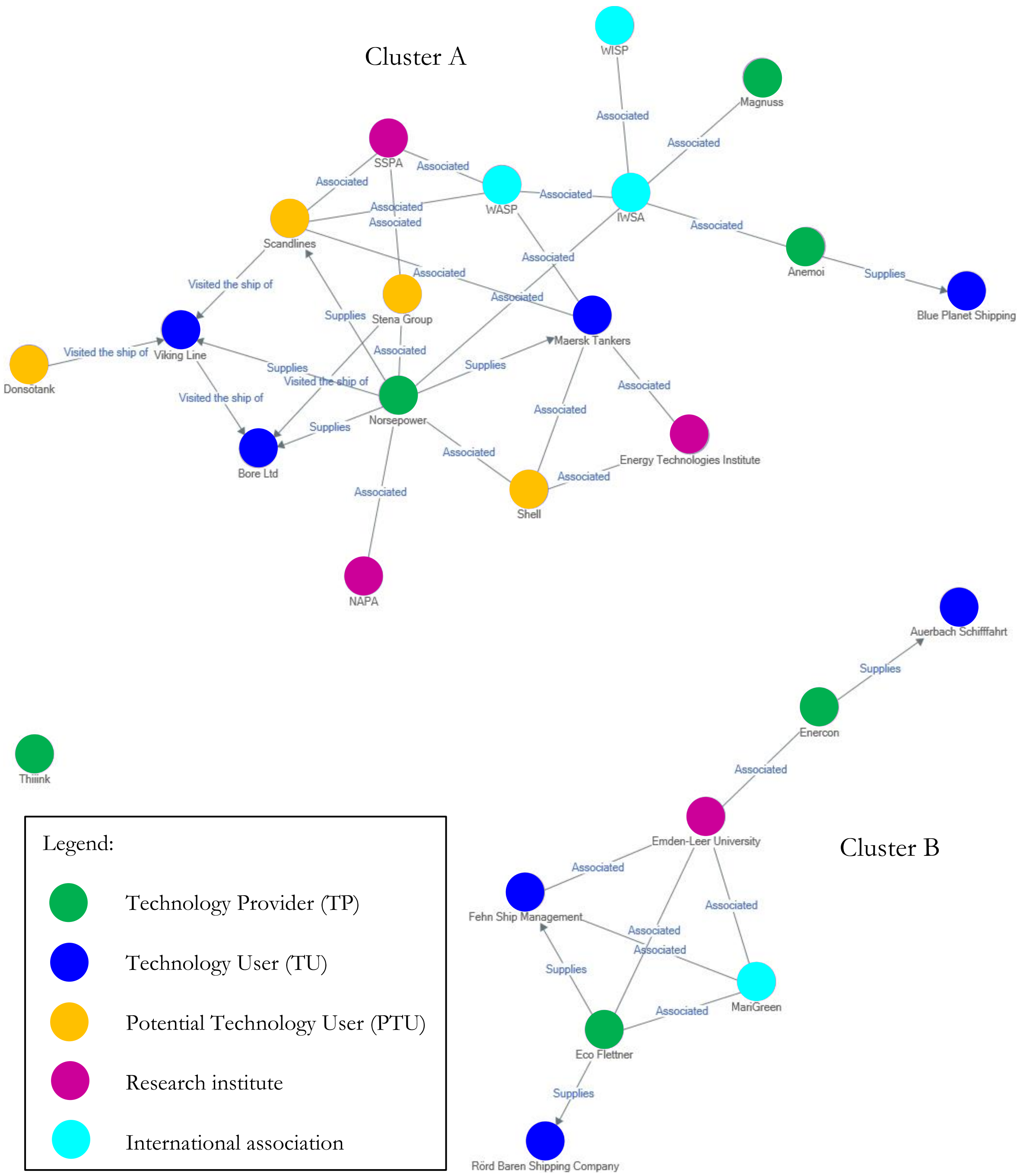

Figure 4-1 'An organisational network map of the Flettner rotor innovation system'. Sources: See Table 4-1 to Table 4-5.

The data collection revealed a network of 23 organisations, divided into two separate clusters: Cluster A, comprising of fifteen organisations and Cluster B, formed of seven organisations. Each cluster contains a mixture of TPs, TUs and PTUs as well as research organisations and international associations. One organisation is an outlier, with no evidence of connections to the others.

Cluster A has a high degree of relationships between organisations, mainly centred around Norsepower supply to four shipowners and association with various PTUs. Its membership of the IWSA brings it into indirect communication with the TPs Magnuss and Anemoi, the latter forming a branch to the cluster by supplying shipowner Blue Planet Shipping.

Every organisation identified is based in Europe, except Magnuss. Two distinct hubs can be identified in Northern Europe wherein actors are densely grouped. Almost every organisation in Cluster B is located in the ports of Emden and Leer in North Germany, forming hub for FR innovation in this area. Some TPs and TUs in Cluster A, namely Norsepower, Viking Line, Bore and NAPA, are grouped around Southern Finland, forming another hub.

Technology Providers (TPs)

Table 4-1 'A list of Technology Providers in the Flettner rotor innovation system'

Name	Location	Details
Anemoi	UK	Supplies Blue Planet Shipping with 4 rotors on a new build bulk carrier, using the Rail Deployment System for bulk carrier cargo loading/unloading (TP-1). Plans to install 8 rotors on a gearless bulk carrier using the Transverse Rail Deployment System (Anemoi Marine, 2020). Developed four types of FR for different operational requirements: Fixed Deployment System, Longitudinal Rail Deployment System, Transverse Rail Deployment System and Folding Deployment System (Anemoi Marine, 2020). Connected to Cluster A through membership of the IWSA (IWSA, 2020a).
Eco Flettner	Germany	Supplies Fehn Ship Management with a single fixed rotor (TU-2). Another installation on general cargo ship owned by Rörd Braren Shipping is planned for August 2020 (de Boer, 2020). Worked with Emden-Leer University to develop the FR control system (including automation, crew input, human-machine interaction and system interface) and the training program (TP-3). Was a member of the MariGreen Interreg program (MariGreen, 2018).
Enercon	Germany	A wind turbine manufacturing company that developed the first modern FR system in 2011, supplying Auerbach Schifffarht with 4 fixed rotors specifically designed for the vessel *E-ship 1* (Schmidt, 2013). Has worked on a project with Emden-Leer University in the past (TP-3).
Magnuss	USA	Developed the Vertically-variable Ocean Sail System (VOSS) retractable FRs but so far has none installed (IWSA, 2020a). Connected to Cluster A through membership of the IWSA (IWSA, 2020a).
Norsepower	Finland	Supplies three shipping companies with standard fixed rotors: Viking Line, Bore and Maersk Tankers (TU-1). Another three installations are ongoing: one FR on a RoPax vessel operated by Scandlines, two FRs on a cargo vessel and another delivery which is not yet publicly disclosed (TU-1). Worked with Shell and Maersk Tankers to "talk to main port [authorities] and debunk FR fears and misconceptions" (TU-3). Worked with NAPA to verify fuel savings for the *M/S Viking Grace* and *MV Estraden* (TP-1). Is a member of the IWSA (IWSA, 2020a). The most connected actor in the network (7 relationships) and largest TP (3 installations), Norsepower is the nexus of Cluster A and has associations with various actor types.
Thiiink	Switzerland	Has developed a foldable FR system called the Folding Flettner Rotor Wing but so far has no operational installations (THiiiNK, n.d.). The TP is an outlier and has no associations with other organisations.

Technology Users (TUs)

Table 4-2 'A list of Technology Users in the Flettner rotor innovation system'

Name	Location	Details
Auerbach Schifffahrt	Germany	Operates 4 rotors since 2011 supplied by Enercon on the *E-ship 1*, a 12,700 dwt general cargo/RoRo vessel (Enercon, 2013). Sailing on irregular routes worldwide, it has saved 920 tonnes of fuel per year, or approximately 15%, calculated at a cruising speed of 13 knots (TP-4).
Blue Planet Shipping	Greece	Operates 4 rotors supplied by Anemoi using the Rail Deployment System for bulk carrier cargo loading/unloading on the *MV Afros*, a 64,000 dwt geared bulk carrier operating global, irregular routes on short-term charters (Anemoi Marine, 2020).
Bore	Finland	Operates 2 rotors since 2014, supplied by Norsepower on the 9,700 dwt RoRo vessel *MV Estraden* with verified fuel savings of 400 tonnes per year, or 6%, on a regular route in the North Sea (TP-1). As an early FR adopter, PTUs Viking Line (before their installation) and Stena Group visited this ship to inspect and inform future installations (TU-1; PTU-3).
Fehn Ship Management	Germany	Operates a FR supplied by Eco Flettner since 2018 on the 4,500-dwt general cargo vessel *M/S Fehn Pollux*, with fuel savings of 10-15% sailing in irregular routes around European coasts (TU-2). Emden-Leer University developed software and training (TP-3). Was partner in the MariGreen Interreg project (TU-3).
Maersk Tankers	Denmark	Operates two Norsepower-built prototype FRs on a 109,000-dwt long range (LR) tanker vessel *Maersk Pelican* with verified fuel savings of 8.2%, or about 500 to 750 tonnes per year, over a year of global spot trading on irregular routes (TU-3). Regularly communicates with Scandlines, a non-competitor with a similar upcoming installation (PTU-1; TU-3). FRs were chosen in collaboration with ETI and Shell and the installation was subsidised by ETI and WASP Interreg contributions (TU-3; IWSA, 2020b). Worked with Shell and Norsepower to "talk to main port [authorities] and debunk FR fears and misconceptions" (TU-3). Verification of fuel savings was conducted by ETI (TU-3). Is a member of the IWSA (IWSA, 2020a).
Viking Line	Finland	Operates a single FR since 2018 supplied by Norsepower on the 57,000 GT / 2,800 passenger RoPax vessel *M/S Viking Grace*. Verified fuel savings are 230 to 320 tonnes per year, or 1.5%, sailing on a regular route between Stockholm, Sweden and Turku, Finland through the Stockholm and Åland Archipelagos (TP-1; TU-1). Has enabled ship visits to the *Viking Grace* by PTU senior staff from Scandlines and Donsötank (TU-1; PTU-1; PTU-2). Viking Line employees themselves visited Bore before installing a FR "out of curiosity" (TU-1).

Potential Technology Users (PTUs)

Table 4-3 'A list of Potential Technology Users in the Flettner rotor innovation system'

Name	Location	Development stage	Details
Rörd Braren Shipping	Germany	Under construction	Awaiting one FR installation on the 5,000 dwt general cargo vessel *Annika Braren* in August 2020, supplied by Eco Flettner (de Boer, 2020).

Scandlines	Denmark	Under construction	Awaiting one FR installation on the 5,000 dwt RoPax vessel *Copenhagen* in the second quarter of 2020, supplied by Norsepower including a service and maintenance agreement (PTU-1; Scandlines, 2018). In regular communication with Maersk Tankers and SSPA (TU-3; PTU-1). Visited the Viking Line vessel *M/S Viking Grace* (PTU-1). Is a partner in the WASP Interreg project (PTU-1).
Shell	Netherlands	Formerly interested	Initially considered installing FRs on a tanker vessel but decided against it (TU-3). Collaborated informally with Maersk Tankers, Norsepower and ETI to facilitate the *Maersk Pelican* installation (TU-3).
Stena Group	Sweden	Interested	Researching the possibility of installing FRs on vessels in the fleet of Stena's shipping functions (PTU-3). Has regular contact with Norsepower and SSPA (PTU-3). Visited the Bore vessel *MV Estraden* (PTU-3).
Donsötank	Sweden	Formerly interested	Initially considered installing FRs on a tanker vessel but decided against it (PTU-2). Visited the Viking Line vessel *M/S Viking Grace* (PTU-2; TU-1).

Research institutes

Table 4-4 'A list of research institutes in the Flettner rotor innovation system'

Name	**Location**	**Details**
Emden-Leer University[4]	Germany	A maritime university in Northern Germany which developed the control system (including automation, crew input, human-machine interaction and system interface) and the training program for Fehn Ship Management in collaboration with Eco Flettner (TP-3). Previously worked with Enercon (TP-3). Was a partner of the MariGreen Interreg program (TP-3)
Energy Technologies Institute (ETI)	UK	Former public-private partnership between energy companies and the UK Government, now replaced by the Energy Systems Catapult and other organisations (ETI, 2020). Collaborated informally with Maersk Tankers, Norsepower and Shell to facilitate the *Maersk Pelican* installation (TU-3).
NAPA	Finland	Maritime software developer and data analysis institute (NAPA, 2019) which worked with Norsepower to verify fuel savings for the *M/S Viking Grace* and *MV Estraden* (TP-1).
SSPA	Sweden	Maritime research institute and consultancy which is has regular contact with Scandlines and Stena Group and is a partner of the WASP Interreg program (PTU-1; PTU-3; Werner et al., 2020).

[4] In the citation labels, Emden-Leer University is treated as a TP (see Table 3-1) because it developed the FR control system and training program for Fehn Ship Management (TP-3).

International associations

Table 4-5 'A list of international associations in the Flettner rotor innovation system'

Name	Description
International Windship Association (IWSA)	Trade association that "facilitates and promotes wind propulsion for commercial shipping worldwide" (IWSA, 2020a, p4) through improving communication, lobbying, project development and promotion. Has over 120 members, including stakeholders Anemoi, Magnuss, Norsepower, Maersk Tankers and associated projects WASP and WISP (IWSA, 2020a).
MariGreen	Interreg project that ran until 2018, funded by the ERDF and local municipalities in the Ems-Dollart Region. Included engineering and design of a FR vessel (MariGreen, 2019a), voyage modelling and optimisation (MariGreen, 2019b) and the installation of a FR on the *Fehn Pollux* (TU-2). Members included Fehn Ship Management (TU-2), Emden-Leer University (TP-3) and Eco Flettner (TU-2).
WASP	Ongoing Interreg program bringing together TPs, shipowners and research institutes in the North Sea Region to develop knowledge of wind propulsion technology and provides access to ERDF financial resources totalling 5.4€ million (IWSA, 2020b). Aims to create standard performance indicators to determine the most beneficial contexts for wind propulsion (including FRs), allowing for comparison across technologies and reference projects (PTU-1). Includes an installation of a FR on the Scandlines vessel *Copenhagen* (PTU-1). Members include Scandlines (PTU-1), Maersk Tankers (TU-3) and SSPA (IWSA, 2020b) and the program is associated with the IWSA (IWSA, 2020b).
WISP	Ongoing joint-industry partnership to create performance indicators for wind propulsion and recommend changes to regulations (Marin, 2019). The project is in an early phase and the partners are as yet unclear beyond it being coordinated by research institute Marin in collaboration with the regulator ABS, an institutional actor (Marin, 2019).

4.1.1.2 Institutions

Formal institutions

The highest-level formal institutions relevant to the FRIS are the IMO and the EU (IWSA, 2020b). Shipowners and TPs are impacted by regulations decided by these bodies and a reciprocal, but smaller interaction occurs from FR organisations towards these institutions in shaping the debate on maritime decarbonisation (IWSA, 2020b).

At a more local level, national authorities interpret IMO regulations and port authorities produce regulations specific to port activities (TU-3; PTU-1). There is direct interaction between these bodies and FRIS organisations in the form of communication and lobbying from PTUs and TPs (TU-2; TU-3).

Classification societies are formal institutions which approve vessels for seaworthiness, based on risk assessments and inspections to ensure that maritime standards and regulations are adhered to (TP-1). All installed FRs adhere to maritime standards as prerequisite conditions, covering their design, manufacture, operation and maintenance (TP-2; TU-1; TU-3). TPs, TUs and classification societies such as Lloyds Register and DNV GL collaborate to conduct a comprehensive risk assessment before each installation (TP-1; TP-2; TU-1; TU-2; TU-3; PTU-1; PTU-3). Reference projects have helped to produce standards for FRs which guide classification for future FR installations (PTU-1; PTU-3).

As auxiliary propulsion, FRs are characterised as "non-essential deck equipment" (TP-2) by classification societies and receive approval without difficulty, apart from minor risk mitigation efforts sometimes being required on a case-by-case basis (TP-1; TU-2). Higher standards are required on tanker vessels which are extremely sensitive to static electricity on deck which could cause sparks, igniting fuel cargo (TU-3). Accordingly, FRs are EX/ATEX Directive-approved to ensure no static electricity is produced from rotation and all electrical hardware is placed aft, off-deck with the engine components (TU-3).

Classification society ClassNK has produced guidelines concerning safety, navigation and installation requirements for all types of wind assistance technologies and it is expected that all societies will follow by the end of 2020 (IWSA, 2020b). Further development towards recognition and standardisation of different societies' guidelines is nonetheless required (IWSA, 2020b).

Informal institutions

The particularities of the shipping industry tend heavily towards conservatism throughout all actors concerned (TU-3). Informal constraints are governed by the attitudes of the close-knit community of shipowners (TP-2) and the expectations and requirements of contractors (TU-2; PTU-2). Contractors of vessels carrying cargo or passengers boarding ferries demand reliability and punctuality which influences the decisions of shipowners (TU-3; PTU-2).

Shipping companies want to have confidence in new technologies, meaning performance, reliability and safety must be proved in operation before shipowners consider investing (TP-2). Thus, reference projects are extremely important (TP-1; PTU-3) but many actors remain uncomfortable with the technology and many misunderstandings exist among shipowners (TU-1; TU-3). Nonetheless, there is tangible momentum building around FRs through growing interest (TP-2).

4.1.2 Dynamics

4.1.2.1 Function 1: entrepreneurial activities

The mapping of new entrants into the modern FRIS can be traced back to before 2011 with the development of FRs by Enercon and the launch of the *E-ship 1* (Enercon, 2013). Of all the organisations identified in the network (see Figure 4-1), TPs are the only new entrants from a FRIS perspective, in that they were created solely to develop and innovate FR technology. The other actors, be they shipowners, research institutes or international associations are linked to the incumbent regime and are concerned, for the most part, with matters outside of the FRIS. An exception is Enercon, which is chiefly a wind turbine manufacturer but diversified into FR production. By this definition, the number of new entrants into the IS since 2011 equals the number of TPs at six.

Shipowner motivation to install FRs is primarily reduction of fuel costs (TU-3; PTU-1; PTU-3; TP-1; TP-2; de Boer, 2020) but also to reduction of CO_2 emissions (PTU-1; PTU-3; TP-1; TP-

2; Enercon, 2013) and increased publicity for being environmentally conscious and at the forefront of technological innovation (TU-1; TU-2; TU-3; TP-1; TP-2).

The most important variable influencing shipowners' decisions to install FRs is the payback time, in years (TU-1; TU-3; PTU-3). This is the return of investment, or breakeven point, of a FR installation based on the resulting fuel costs savings (TU-1; PTU-3). The payback time is thus a function of fuel reduction and installation costs and the better the fuel saving performance, the shorter the payback time.

All eight shipowners with installed FRs or plans to install FRs are chiefly reliant on the incumbent regime of traditional propulsion to fulfil their essential functions. However, they have freely chosen to diversify their propulsion using FRs and thus can be mapped as entrepreneurs. These include two organisations heavily immersed in the incumbent regime: Maersk Tankers and Shell. Both shipowners are associated with larger energy companies involved in the extraction, production and transport of hydrocarbons but have involved themselves in FR development and, in the case of Maersk Tankers, installed FRs on board a vessel (TU-3).

4.1.2.2 Function 2: knowledge creation

R&D projects, such as MariGreen, WASP and WISP, are taking place in the wind propulsion IS which produce knowledge benefitting all technologies, such as ship designs for wind propulsion, route optimisation and performance validation (IWSA, 2020b; MariGreen, 2019b, 2019a). TPs also perform independent R&D projects to continually optimise FR design and operation (TP-1; TP-2).

A diverse variety of FR types are patented by TPs (see Figure 4-2). Each TP holds patents for their FR designs, the standard being fixed rotors which vary in size from 18 x 3 m to 30 x 5 m (TU-2; TU-3). Alternative FR designs, such as displaceable, foldable (or tiltable) and lowerable (or telescopic) FRs, enable fulfilment of specific ship requirements.

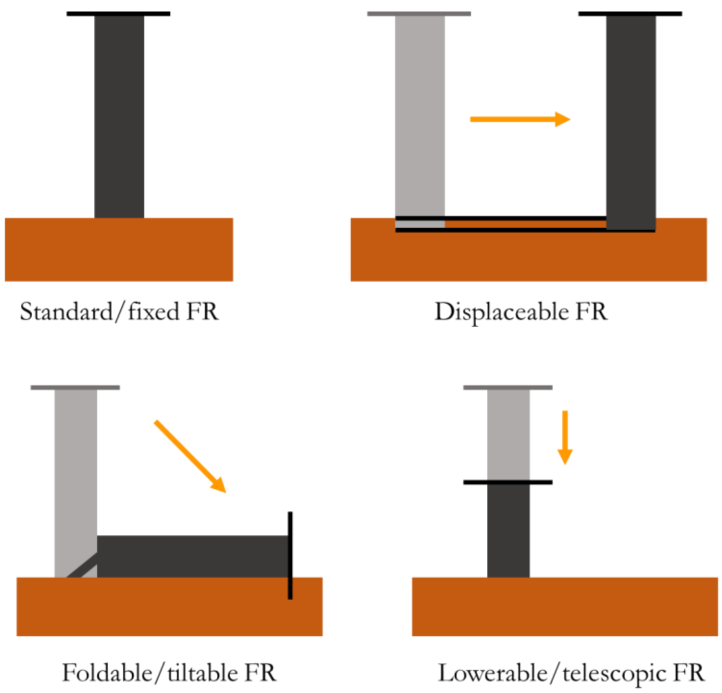

Figure 4-2 'Types of Flettner rotors'. Source: Author's own work.

Displaceable FRs are designed to fulfil specific cargo loading and unloading requirements, such as Anemoi's Rail Deployment System for the bulk sector (TP-2). Foldable and lowerable FRs reduce a vessel's air draught, enabling access through waterways or under port infrastructure. Examples of these solutions are Anemoi's Raising and Lowering Deployment System (Anemoi Marine, 2020), Magnuss VOSS (IWSA, 2020a) and Thiiink Folding Flettner Rotors (THiiiNK, n.d.). Norsepower has expressed interest in developing their own foldable FR (Kuuskoski, 2018).

Learning by doing is advancing steadily for FRs, with six vessels operating fourteen FRs between them (de Boer, 2020; IMO, 2020). Standard FRs are the most advanced type, comprising five out of six of the operational installations and two more installations upcoming (de Boer, 2020; IMO, 2020). The only 'alternative FRs' in operation are four displaceable FRs developed by Anemoi, installed on the Blue Planet Shipping vessel *MV Afros* (TP-2). All existing rotor vessels are important reference projects which produce learning by doing from operational experience (TP-1).

4.1.2.3 Function 3: knowledge diffusion through networks

The leading trade association for wind propulsion technologies, the International Windship Association (IWSA), has grown to over 120 members including experts, key stakeholders and policy makers (IWSA, 2020a). The association aims to facilitate networking in the sector through conferences and its newsletter and to promote relevant information and achievements to the wider shipping industry (IWSA, 2020a).

Conferences are very important interaction events which bring together many actors both from within the FRIS and from outside sectors (IWSA, 2020b). Conferences specifically devoted to wind propulsion technologies, such as the International Wind Propulsion for Shipping Forum and the International Conference on Wind Propulsion, both in association with the IWSA and the latter organised by the Royal Institute of Naval Architects (RINA), see many shipowners, TPs, researchers, financers, regulators and entrepreneurs meet to discuss and share the state-of-the-art knowledge in FRs and other wind propulsion technologies (IWSA, 2020b; RINA, 2019b). Subjects discussed at conferences have wide impacts on stakeholders outside of the FRIS, with findings reaching important institutional actors such as the IMO and EU (IWSA, 2020b).

Interactions between non-competitor shipowners, such as between Scandlines and Maersk Tankers (PTU-1; TU-3), occur to gain knowledge of the latest FR developments. PTUs are able to gain information about FR installations, in order to draw comparisons for future installations (PTU-1). The relationship is reciprocal; as well as providing experience to PTUs, TUs can also gain experience from the PTU post-installation (TU-3).

Ship visits are a type of interaction that enables the sharing of operational knowledge between shipping companies (PTU-1; PTU-2; PTU-3, TU-1; TP-1). Visits are common the industry, especially with new or unusual technologies (PTU-1) to learn from peer organisations about safety, reliability and operation (TP-1; TP-2), strengthen intra-organisational communication (TU-1; PTU-1) or simply out of curiosity (TU-1). Ship visits usually only take place if shipping companies are not direct competitors and they are in communication with the same TP. PTUs may board a TU's vessel to gain user-end experience, informing their decision to install FRs or not (TP-1). An example is Viking Line staff visiting the installation on Bore's vessel *MV Estraden* (see Figure 4-1) before installing a FR on the *M/S Viking Grace*. The companies are not direct competitors, Viking Line being a passenger ferry operator and Bore being a freight trafficker. Furthermore, each ship operator is in communication with Norsepower, Bore because they were supplied by them and Viking Line because they were investigating a potential installation by Norsepower.

Industry partnerships are another important medium for knowledge transfer through the FR network. Examples can be formal, such as the MariGreen and WASP EU programs and the WISP joint-industry project (TU-2; IWSA, 2020b), or informal like the collaboration of Maersk Tankers, Shell and ETI (TU-3).

4.1.2.4 Function 4: guidance of the search

There are no policies directly aimed at supporting the uptake of FRs or wind propulsion technology in general. However, a recent indication of development towards specific policy for wind propulsion was the IMO's adoption of the Comoros resolution 74(26) to the MEPC (IWSA, 2020b).

Fuel saving expectations of PTUs vary between shipowners, with Scandlines and Stena Group expecting modest savings of about 3 to 5% per rotor (PTU-1; PTU-3) and Rörd Braren Shipping expecting up to 15% (de Boer, 2020). This is similar to the IMO's figure of 5 to 20% (IMO, 2020), given that percentage savings depend greatly on the vessel concerned (TP-1). The fuel saving outcomes of installed FRs compared to expectations varies by TU; Viking Line is underwhelmed with 1.5% savings, having expected 3% (TU-1), while Fehn Ship Management had little or no expectations for fuel savings and has arrived at 10 to 15% (TU-2).

Verification of fuel savings data can be produced by independent third-party bodies for TPs and TUs, such as NAPA, Lloyds Register, ABB and ETI. (TP-1; TU-1; TU-3). However, there is not yet a standardised approach to fuel savings calculations and so values are extremely difficult to compare across cases (TP-1).

Expectations of FR operation are justifiably high. They are reliable, safe, easy to install and simple to operate and maintain (TP-1; TP-2; TP-3; TU-3; PTU-3; Enercon, 2013). One interviewee described them as "not rocket science" (TU-3). When compared with other wind propulsion technologies, FRs do not produce fuel savings quite as high as kites or hard sails, but are much simpler to use, more robust (TU-2; TU-3; PTU-3; de Boer, 2020) and more compact, yielding the highest thrust per sail area (TP-1). Furthermore, existing reference projects contribute to a reputation of FRs being a "proven technology" (TP-1; PTU-3).

4.1.2.5 Function 5: market formation

Current IMO and EU maritime standards do not limit GHG emissions but FRs offer an opportunity for ships to anticipate and comply with future environmental regulation (TP-2). FRs compete in a niche market with other technologies that offer emissions reductions, such as Controllable Pitch Propellers (CPP), efficient hull design and fuels such as Liquid Natural Gas (LNG) and Marine Gas Oil (MGO) (TP-1; Enercon, 2013). However, competition is not direct because they can be installed in addition to them, as shown by the vessels *E-ship 1* and *M/S Viking Grace* (TP-1; Enercon, 2013).

FR uptake is motivated by anticipation of future economic benefits for emissions reductions, such as lower port fees or an ETS (TP-2; TU-3; PTU-3). Discounts on port fees for vessels with low GHG and air pollutant emissions and high safety standards are provided by the Green Award, a voluntary certification offered by large ports in twelve countries around the world

(Green Award Foundation, 2018). Originally designed to reduce SO_2 and NO_x emissions, the certification was expanded to include CO_2 as of March 2020 (Green Award Foundation, 2020a). However, no vessels with FRs have yet been certified (Green Award Foundation, 2020b).

4.1.2.6 Function 6: resource mobilisation

The FRIS has benefitted from government and EU financial resources to fund installations (TP-2), with all FR installations to date having received aid in some form (TP-1; TP-2). For example, MariGreen and WASP mobilised ERDF resources to directly fund FR installations on the Fehn Ship Management and Scandlines installations respectively (TU-2; PTU-1) and the UK Government provided funding for Maersk Tankers via ETI (Bradley, 2017). Standalone FR installations, such as those of Viking Line and Rörd Braren Shipping, received substantial EU subsidies funding 50 to 60% of the project costs (de Boer, 2020; European Commission, 2018). The IWSA plays an important role in helping stakeholders secure funds (IWSA, 2020a).

4.1.2.7 Function 7: creation of legitimacy

Lobbying action is occurring to convince institutions to facilitate policies, activities and funding in favour of FR interests (IWSA, 2020a). Before the *Maersk Pelican* installation, the main ports of call concerned and the flag authority (Singapore) required lobbying to demystify FRs and reduce institutional fears surrounding the technology (TU-3). Maersk Tankers formed a coalition of interest groups comprising of itself, Shell and ETI who successfully lobbied port authorities and flag authorities (TU-3). Flag authorities are particularly powerful because they interpret IMO regulations (TU-3) and FRs have yet to be included in EEDI calculations, only hard sails (IMO, 2019). However, lobbying is not necessarily required; in the case of the *Fehn Pollux* installation, port authorities were enthusiastic about FRs and willing to facilitate the project (TU-2). The IWSA engages in lobbying and advising of legislators to facilitate wind propulsion retrofits and new builds (IWSA, 2020a).

The reaction of interest groups in the incumbent regime to FR development is mixed. In the *Maersk Pelican* installation, the oil company Shell were enthusiastic to collaborate with Maersk Tankers and Norsepower (TU-3). However, in the cases of Donsötank and Stena Teknik (researching on behalf of Stena Tankers), FR installations on tanker vessels were dissuaded due to industry norms of encouraging fast vessel turnover, as dictated by oil company policy (PTU-2; PTU-3). Large oil companies have great influence over tanker companies because they can demand safety requirements and not approve older vessels despite their long lifespans (TU-3; PTU-3). Current return-of-investment for FRs on tankers is thus uneconomical at 7 to 12 years, despite vessel lifespans of 30 to 40 years (PTU-3).

4.1.2.8 Interaction of functions

The only function interaction clearly identified by interviewees was that the funding of FR installations increases the number of reference projects, increasing learning by doing and increasing shipowner confidence in the technology (TP-1; TP-2). In other words, mobilised resources (F6) are directed towards installations which drive learning by doing (F2), in turn increasing expectations of the technology (F4), as shown in Figure 4-3.

Figure 4-3 'A linear function interaction in the Flettner rotor innovation system, as identified by respondents.' Source: Author's own work.

The interactions identified by the respondents are wholly positive, indicating a trend of growth for the FRIS. However, the proposed model is linear and is thus incomplete. A possible circular interaction of functions is discussed in Section 5.1.3.

4.2 Findings from Operational Experience

4.2.1 Technical Impacts on Vessel Operations

Technical impacts, in this thesis, are the physical changes on board a ship that are directly caused by the existence of FR(s) on board. The operational experience of interview respondents is documented to create a list of technical impacts of FRs on vessel operations (see Table 4-6). Each impact is explained and its significance for vessel operations described. If they are found to be significant depending on certain variables, or conditions, those are explained as well as the solution(s) to mitigate each impact, as described by the respondents. A more detailed explanation of each impact is given further on in this section.

Table 4-6 'List of FR technical impacts on vessel operations'

Impact	**Significance**	**Variable(s)**	**Details**	**Solution(s)**
Drifting and heeling	None to moderate	Route Rudder size Bow thruster power	Affects routes with many manoeuvres. No impacts when in open sea or in port.	Automatic idle mode in critical manoeuvres. Ensure rudder size and bow thruster power are adequate.
Noise and vibrations	None	-	Some minor effects due to early prototype design but had no impact on operations.	-
Access to waterways	None to severe	Bridge height Route	May increase air draught on ships with low bridge heights. Usually only affects small vessels. Prevents operations in routes under bridges or berthing below warehouses.	Analyse all possible ports and berths prior to installation. Install foldable or lowerable FRs if access required.
Cargo handling	None except for container ships	Ship type FR type	Standard FRs have no impact for RoRo, RoPax, general cargo and tankers. Displaceable FRs available for bulk carriers. No solution yet devised for container or offshore supply ships.	Ensure correct FR type for ship type.

Passenger comfort	None	-	No impact even with early prototype noise and vibrations.	-
Visibility	None to manageable	FR location	Bridge visibility impacted if FR located below bridge height.	Install additional radar to cover blind spot.

4.2.1.1 Drift and heeling

FR rotor towers increase a ship's air resistance, which, in extreme wind conditions, may produce a drag force causing a drift force and increasing the vessel's effective width (TU-1; TU-3; PTU-1; PTU-3) or a heeling effect (TU-1; TU-2; PTU-3) that can impact rudder control (TU-1).

Operational experience on the *Fehn Pollux* (TU-2) and *Maersk Pelican* (TU-3) found no evidence of such effects impacting manoeuvres. In fact, it is even claimed that FRs increase ship stability (Enercon, 2013; MariGreen, 2019a). However, the Captain of the *Viking Grace* could detect a drag force when performing manoeuvres in strong winds which could be stabilising or detrimental: "sometimes it is advantageous, sometimes not" (TU-1). Furthermore, the Pilots noticed a heeling effect due to the FR in strong winds, reducing rudder control and impacting turns (TU-1). The extent of these effects is difficult to quantify because of the variety of interacting factors at play, but are insignificant when at open-sea (TU-1).

The impact of drift and heeling on manoeuvres is reduced up to a point by 'reefing'; reducing rotation speed to very low to incur minimum drag (TP-1). For Norsepower's systems, reefing is known as 'idle mode' and consists of the rotor column slowing to about 3 rpm (TP-1; TU-1). In unfavourable wind conditions, such as headwinds or periods of fast-changing wind direction, the FR automatically switches to idle mode, reducing drag and heeling (TP-1; TU-1). Drag and heeling are completely removed by designing larger rudders and suitable bow thruster power (TU-1; PTU-3). However, this solution is only available for new builds as it is difficult to retrofit (PTU-3).

4.2.1.2 Noise and vibrations

As an auxiliary propulsion system, FRs are completely separate from the main engine (TU-2; TU-3), running on power from on-board generators to drive electric motors located within the column structure (TU-1; TU-3; Enercon, 2013). Being rapidly spinning mechanical devices, FRs can produce vibrations and noise if there are irregularities with the column structure or bearing faults (TU-1). If any mechanical issues occur, they can be handled by switching off the device(s) to perform maintenance without impacting vessel operations (TP-1).

Noise due to the FR was found to be insignificant (TU-1; TU-2). While the crew of the *Viking Grace* could identify a "low, mechanical whirring" inside the ship, directly underneath the FR, it was not easily identifiable over the din of the general noise emanating from the ship's engine (TU-1).

Generally, vibrations caused by FRs are described as "normal" and posed "no problem" (TU-2). Norsepower designs FRs to enter idle mode automatically if unusual vibrations are detected (TU-1) and the crew monitors vibrations (TU-1). Neither noise or vibrations from FRs cause no impact on crew comfort, according to both shipowner (TU-2) and crew (TU-1).

A prototype issue had caused bearings to wear out earlier than expected, producing some noise and unusual vibrations (TU-1). This was quickly recognised and fixed (TP-1; TU-1), without any impacts on passenger or crew comfort (TU-1).

4.2.1.3 Access to waterways

Accessibility of certain waterways may be restricted if the installation of an FR increases a vessel's air draught (TU-1; TU-2; TU-3; PTU-3). The bridge crew must be aware of the navigational limitations, such as passing under bridges, electricity cables or entering berths with port infrastructure overhead when planning a route (TU-1; TU-2).

Shipowners have considered this issue in advance and ensured that any hindrance to accessibility has no impact on vessel operations (TU-1; TU-2). For example, there are about 10 ports in Europe that became inaccessible since the *Fehn Pollux* installed a FR (TU-2). The shipowner identified this issue beforehand and concluded that the inaccessible locations are not major ports, so vessel operations is not impacted (TU-2).

However, there was a planned installation by Fehn Ship Management on small ship with a low bridge height which was cancelled due to the increased air draught with the FR (TU-2). This meant many ports would be inaccessible due to bridges and port infrastructure such as warehouses above berths (TU-2). For this reason, an analysis of all ports and berths where a ship would operate is conducted prior to any installation (TU-2).

4.2.1.4 Other impacts

Impacts on cargo handling are none for almost every standard ship type due to the available FR designs for different cargo loading and unloading requirements. Standard FRs have no impact on cargo handling for general cargo ships (TU-2), tankers (TU-3) or RoRo ships (Enercon, 2013). In the case of bulk carriers, which have particularly challenging loading and discharging operations, alternative FR systems ensure that crew workload is minimised and cargo handling is unaffected (TP-2; IWSA, 2020a; THiiiNK, n.d.). The first operational example is the *MV Afros* which is installed with the Anemoi Rail Deployment System (TP-2). Two exceptions are container shipping, where a lack of deck space and unloading and loading using overhead cranes makes FRs, in their current forms, unfeasible (TU-3) and offshore supply ships.

There is no impact on passenger comfort, based on experience from the *Viking Grace* (TU-1). Even when prototype issues caused increased noise and vibration, there was no record of any passenger complaints (TU-1). Furthermore, the ship's heeling has had no impact on passenger comfort either (TU-1).

FRs can impact bridge visibility if located on the ship's platform but in all cases, this is relatively inexpensive to address by installing an extra radar on the bow (TU-2; TU-3). Other additional equipment may be required due to a FR system, such as wind sensors (TU-1). On passenger vessels such as the *Viking Grace*, the FR is protected by fencing and monitored with CCTV to prevent access by unauthorised personnel (TU-1).

4.2.2 Human Factors in FR Operation

A number of aspects of human-FR interaction are documented, based on operational experiences of respondents. The variables, or conditions, which determine whether each factor causes issues for crew members or not are identified. Finally, some findings specific to the *M/S Viking Grace* are described, based on the usability assessment conducted on board.

4.2.2.1 Automation

All TPs with operational FRs have designed them to be completely automatic, insofar as rotation speed and direction is automatically adjusted based on real-time data for wind speed and direction (TP-1; TP-2; TP-3; Enercon, 2013). Thus, the FR system automatically extracts the maximum thrust available from the existing wind conditions. Fuel consumption, however, is not automated and remains fully influenced by the 'sailing' attitudes and ability of the bridge (TP-3).

Automation is a standard expectation of shipowners considering new technologies (TP-2) and causes any additional bridge crew workload to be greatly reduced (TP-2; TU-1). Onboard or onshore software analyses the data to remotely control the FR, without any crew input required (TP-1; TP-2; TP-3; Enercon, 2013). FRs can nonetheless be manually controlled if desired but this is rarely used, if ever (TP-1; TP-3; TU-1; TU-3). Furthermore, pre-set sequences of automatic switching on and off can be programmed into regular routes to anticipate drifting or heeling impacts and mitigate them by reefing (TU-1). This can produce particular impacts on bridge crew workload, as explained in Section 4.2.2.5.

4.2.2.2 User interface

In general, the user interface is simple and easy to use and consists of control panels and display panels (TU-1; TU-2). Control panels allow bridge crews to manually operate FR systems if required (TP-3; TU-1; TU-3) but, due to automation, manual control of rotor movements is almost never required (TU-1; TU-2). Display panels are provided on the bridge and in the engine control room showing FR information relevant to each crew group (TU-1). Typically, the bridge display panel presents values for environmental conditions, FR rotation speed and direction, resulting thrust force due to the FR and fuel consumption/savings (TU-1; TP-2; Enercon, 2013; MariGreen, 2019). The engine room panel displays mechanical data relevant to inspections and maintenance work and performance data (TU-1).

On the *M/S Viking Grace* bridge, the FR control panel is rectangular, about 15 cm tall by 30 cm wide, and is located at about 3 o'clock from the co-pilot's chair, slightly out of arm's reach. It contains the following controls (TU-1):

- An emergency stop button. Two more of these are located elsewhere on the ship: one in the engine control room and one beside the FR on Deck 13.
- A button for autopilot mode. It places the FR in automatic operation, with rotation speed and direction determined by wind conditions. This is mode is used most often.
- A button for idle mode. The crew uses this to manually place the FR into idle mode outside of red zones when performing critical manoeuvres in strong winds.
- A button for manual control, enabling the crew to control the FR using the lever.
- A temporary notice informing the pilots when the ship is inside a red zone.
- A lever for manually adjusting the FR rotation speed (from 0 to 220 rpm) and rotation direction (clockwise or anticlockwise). This had been used only once (TU-1).
- A button to acknowledge alarms. The bridge interface produces an inaudible flashing alarm for numerous reasons, including when wind speed exceeds 27 m/s (TU-1).

The engine control room display panel on the *Viking Grace* presents the following FR maintenance and performance data (TU-1):

- Bearing temperature and vibrations over time;

- Propulsion power savings/consumption over time (per day);
- Fuel savings/consumption over time (per day).

A CCTV camera constantly monitors the FR and can be displayed on a screen in the engine control room. The engine crew have no control over the FR apart from an emergency stop button in the control room. Another emergency stop button is located on Deck 13 at the foot of the FR foundation, in case maintenance personnel must shut it down manually while on-site.

4.2.2.3 Maintenance

The consensus among TPs and TUs is that FR maintenance work is low (TU-1; TU-2; TU-3; TP-1; Enercon, 2013). Any work mostly consists of regular inspection and documentation; actual repairs are very rarely needed if ever (TU-1; TU-2; TU-3; TP-1). Furthermore, maintenance work decreases with time after installation as early prototype issues are addressed (TU-2; TU-3).

The engine crew's maintenance workload depends on whether the TU or TP is responsible for the FR. Workload is higher when the crew is responsible and lower when responsibility lies with the TP (TU-1; TU-2; TU-3; TP-1). TUs are more likely to be responsible for FR maintenance on irregular routes, such as tanker or bulk carrier services (TU-3). On regular routes, such as RoPax and RoRo freight journeys, where onshore mechanics are able to board at specific times and locations, it is more likely that the TP is responsible for FR maintenance. Furthermore, in the prototype and sea-trial phases of an installation, it is likely that the TP retains FR maintenance responsibility (TU-1).

In cases where the TP is responsible for the FR, TP mechanics regularly go aboard to inspect the FR (TU-1). If an issue is detected by engine crew or TP monitoring, the crew halt operation of the FR and TP mechanics perform any repairs required (TP-1). Thus, the vessel's crew perform no maintenance apart from minor checks before repairs (TP-1).

On the *Viking Grace*, responsibility for the FR lies with Norsepower and engine crew work FR work was minimal; the First Engineer doesn't often look at the display panel (TU-1). Norsepower perform constant monitoring of mechanical data onshore and inform the crew if any checks must be made (TP-1; TU-1). Every fortnight, Norsepower mechanics go aboard for 45 minutes deliver spare parts and perform inspections by climbing inside the FR (TU-1). The crew have never had to perform maintenance and in cases where issues do arise, they report directly to Norsepower (TU-1). Such instances are rare and may not occur for several months at a time (TU-1). The crew received "very brief" training, consisting of an introductory explanation of the FR system and a climb inside the rotor column to access the drive motor at 18 metres height (TU-1). Despite the rudimentary training, they feel they have adequate knowledge to maintain the FR themselves if required, but that this would be "demanding work due to the heights and enclosed space" (TU-1). The engine crew possesses the correct safety equipment and certifications to enter the sail but, so far, this has not been required (TU-1).

For crews responsible for the FR, maintenance work is the responsibility of the Chief Engineer (TU-3). Nevertheless, the crew maintain a constant dialogue with the TP and receive detailed inspection and maintenance manuals as well as spare parts if repairs are required (TP-1). Typically, such repairs are not required (TU-2; TU-3; TP-1). Inspection work lasts roughly 1-2 hours per month per rotor, such as checking the rotor column welding seam, checking the oil level and changing oil if required (TU-2). Engine crew enter inside the rotor column and climb up a ladder using harnesses to the motor platform, located at 15-20m height depending on the rotor's size (TU-2; TU-3). Further work includes documenting and verifying possible issues with the FR (TU-3). The FR results in more workload for the engine crew, but the amount is manageable and fully integrated into the existing maintenance schedule (TU-3; PTU-1). If any issues arise that the vessel crew cannot resolve themselves, the TP can step in and perform maintenance (TU-3).

Any additional equipment associated with the FR, such as radar, wind sensors and CCTV, must be inspected and maintained by deck crew (TU-3) but require very little additional work and can easily be integrated into the existing work schedule (TU-1). For example, on the *Viking Grace*, the deck crew occasionally perform 'flushing' of the FR, spraying it with water as part of the normal deck cleaning schedule (TU-1).

4.2.2.4 Management and communication

The impacts of FR systems on the ship management task were found to be minimal. The tasks of allocating crew roles and communication are discussed here.

Each TP offers solutions that require no extra crew members, fulfilling a major expectation of shipowners installing any new technology. However, the service agreement between TPs and TUs considerably impacts the crew's maintenance work. The Chief Engineer on the *M/S Viking Grace* expressed concern that, was it not for the existing service agreement with Norsepower, additional crew may be required (TU-1).

Manageable increases in the bridge and engine crews' communication tasks are required to maintain a healthy dialogue with the TP, particularly when a service agreement exists. FR systems cause a slight increase in communication tasks for the engine and bridge crew. TPs generally maintain close relationships with TU crews, communicating regularly about daily operations and maintenance and exchanging information to improve FR performance (TP-1; TU-1; TU-3). Regular communication occurs remotely via phone or email, while TPs may visit vessels to collect feedback (TU-3). Again, the service agreement influences this task, with contact being more regular for TUs with service agreements.

4.2.2.5 Particular issues on the *M/S Viking Grace*

Automated reefing

Before installing one FR on the *Viking Grace*, Viking Line and Norsepower devised a solution wherein the FR automatically reefs by entering idle mode at pre-programmed areas of critical manoeuvres along the route, named 'red zones' (TP-1; TU-1). Unfortunately, due to miscommunication between the crew and Norsepower, the size of the red zones was reduced without consultation with the bridge crew, resulting in extra workload consisting of checking wind conditions and if necessary, manually placing the FR into idle mode (TU-1). This small increase in bridge crew workload can have a large impact at critical points on the route where minutes, and sometimes seconds, are critical in ship manoeuvres (TU-1).

The effects of heeling and drift are insignificant for open-sea routes, as explained in Section 4.2.1.1. However, the many sharp turns and navigation through narrow channels on the *M/S Viking Grace* route (see Figure 4-4 and Figure 4-5) mean the effects are noticeable (TU-1).

Figure 4-4 'The view from Deck 13 of the M/S Viking Grace *while passing through a narrow channel in the Stockholm Archipelago'. Source: Author's own work.*

Figure 4-5 'An example of the many small islands making up the Åland Archipelago, as seen from on board the M/S Viking Grace'. *Source: Author's own work.*

Furthermore, in very favourable winds, large FRs can cause over-speeding or impeded speed reduction (TP-1; TU-1). In these rare conditions, the FR rotation speed may have to be manually reduced to avoid over-speeding (TP-1). This is particularly significant on the Stockholm – Turku route because the red zones have speed restrictions:

> "Slowing down is very important on the *Viking Grace* route because of the complicated manoeuvres in the archipelago. There is a very tight route schedule where control

sequences must be timed very accurately (to the minute or to the half minute), so small impediments to speed control can be critical." (Safety Officer, TU-1).

Consequently, the pilots conservatively place the FR into idle mode manually, increasing their input into the operation of the system and adding to their workload. In red zones, due to tight schedules and complicated manoeuvres, the pilots are fully occupied with completing checks and other tasks (TU-1). This exacerbates the impact of any additional workload caused due to automated reefing.

Communication with Norsepower

The visit on board the *M/S Viking Grace* revealed some conflict in perception of the magnitude of the communication required between Norsepower and the Viking Line bridge crew. Norsepower perceived the communication task to be small (TP-1) and the engine crew agreed (TU-1), but the bridge crew found they were too busy to maintain contact with the TP to the extent demanded (TU-1).

The Pilots felt that their questions to Norsepower had generally not been satisfactorily answered, particularly concerning the issue of the modified red zones for automated reefing (TU-1). They had given up trying to change the red zones back to their original size because they were used to being ignored (TU-1). Furthermore, the bridge crew felt they had not been properly instructed about the FR fuel savings. The Pilots and Safety Officer wished to see the raw data of fuel savings to better understand Norsepower's calculations (TU-1). Finally, it was never communicated to the crew what the function of FR alarms is (TU-1). The Pilots expressed their interest in seeing a list of different FR alarms in order to understand their causes, something which had never been provided (TU-1).

The combined effect of miscommunication issues with the *M/S Viking Grace* reduced the bridge crew's motivation to operate the FR and, when approached by the TP, requesting they perform tasks to optimise the red zones, they were unenthusiastic and so declined (TU-1).

4.2.3 Variables Influencing FR Performance

The following variables are a non-exhaustive list of factors identified by respondents as determinants of FR performance. Performance is the ability of an installed FR to reduce the fuel consumption of a vessel, and correspondingly reduce GHG emissions. Performance is complex to measure due to the nature of hydrodynamics and interacting forces (TP-1) and this list should by no means be considered definitive or exhaustive. Furthermore, FRs can still result in significant fuel savings despite these variables (TP-2). Table 4-7 summarises each variable and detailed explanations are provided afterwards.

Table 4-7 'List of variables influencing Flettner rotor performance, as identified by respondents'

Variable	**Summary**	**Issues**	**Solution(s)**
Sailing	Fuel savings directly depend on the bridge crew's choice to reduce main engine propulsion power, entirely uninfluenced by FR automation.	Misuse occurs if crews use FRs to increase vessel speed.	See Section 5.2.3.
Power availability	FRs require between 50 and 100 kW of electrical power per rotor for optimal performance, depending on FR size and vessel size.	Retrofitted FRs may operate at sub-optimal rpm.	Manageable with manual control of rotor rpm to avoid generator overload.

	Does not affect new builds or passenger vessels because of excess power availability in vessel designs.		Install a switch between FR and bow thruster power demand to ensure both are never operated simultaneously.
Route	Prevailing wind conditions determine available wind resources. Vessel's operational profile determines ability of FR to extract thrust from wind.	Affects routes with little time spent at open sea and/or many manoeuvres.	Mitigated through prior analysis of vessel's planned route and operational profile.

Sources: See below.

4.2.3.1 Sailing

Human factors are persistent in sailing operations despite full FR automation (IWSA, 2020b). FR performance is greatly influenced by the bridge crew's attitudes to, and usage of, the FR system, in other words, their 'sailing' ability (TP-3). The variables controlling human factor influence on performance and suggestions for improvement are discussed in detail in Section 5.2.3, as well as technological solutions currently in development which aim to improve FR performance.

Automation, as described in Section 4.2.2.1, allows for maximum extraction of thrust or minimisation of drag given the wind conditions, thus producing greater fuel savings than if manually operated (TP-1; TP-2; TP-3; Enercon, 2013). However, this does not shield the system from human factor influence (IWSA, 2020b).

FR fuel saving performance is increased by reduction of the main engine power in favourable winds (TP-1). To achieve this, the FR should not be used to increase vessel speed, instead the bridge crew should reduce the engine power in such conditions and maintain the vessel's service speed (TP-1; TP-3). The ratio of main engine to FR thrust should be determined by the wind conditions (TP-1). However, this procedure is not automated and thus depends entirely on the decisions of the bridge crew (TP-1; TP-2; TP-3; TU-2).

Misuse of FRs can occur on routes with tight schedules, where the captain utilises the extra force produced by wind conditions to gain speed (TU-3; PTU-3). This will result in less-effective, "improper" usage of the system (TP-2). Bridge crews that understand effective FR operation will produce higher fuel savings from the device(s) (TP-3).

4.2.3.2 Power availability

FRs require between 50 and 100 kW of electrical power per rotor at maximum rotation speed, depending on their size (TU-1; TU-2; Enercon, 2013; MariGreen, 2019a). Therefore, the amount of auxiliary power available on board a vessel impacts its FR performance (TU-3). This issue only impacts retrofitted vessels because new builds can incorporate FR power demand into the ship design (TU-3). Furthermore, retrofits on passenger ships are not affected because such vessels are designed with large auxiliary power availability for the hospitality functions on board (TU-3; PTU-1), as demonstrated by the uninterrupted operation of the 70-kW rotor on the *Viking Grace* (TU-1). New builds are also not affected because FR demand is incorporated into design, enabling high maximum FR power demand such as almost 100 kW per rotor on the *E-ship 1* (Enercon, 2013).

The only operational vessels fitting such criteria are the *Maersk Pelican* and *Fehn Pollux*, in which the limitation has been addressed in different ways. On the ten-year-old *Maersk Pelican*, the challenge was described as "manageable" and was addressed by bridge crew occasionally manually controlling the two FR spinning speeds from an ideal 160 rpm to 120 rpm to prevent overloading the ship's generators (TU-3). Further engineering work could increase the power availability if deemed necessary (TU-3). On the *Fehn Pollux*, the FR power consumption (a maximum of 50 kW and an average of 20 to 30 kW) means that the bow thruster and FR cannot be used simultaneously (TU-2; MariGreen, 2019a). Therefore, a solution was devised by Fehn Ship Management and Eco Flettner, whereby a switch was added to the generator between the bow thruster and FR (TU-2). This has no impact on performance because the bow thruster is only used when in port (TU-2).

4.2.3.3 Route

A vessel's route influences FR performance because of the prevailing wind conditions (TP-2; TU-1; PTU-3). Furthermore, factors related to a ship's operational profile, such as the duration of a voyage spent in open sea and the amount of sailing hours have strong effects on fuel savings (PTU-1).

FRs perform best in open sea where the wind direction is steadier, enabling prolonged fuel savings to be achieved (TU-1). This enables shipowners operating regular route traffic, like Bore, Scandlines and Stena Line, to predict optimum routes where winds blow perpendicular to the vessel's direction of travel (TP-1; PTU-1; PTU-3). Regular changes in relative wind direction on routes with many turns, like Viking Line's Stockholm – Turku route, hinder the FR performance because the software cannot keep up with fast changing wind conditions (TU-1).

Vessels on irregular routes with high proportions of open sea sailing can expect strong performance of FRs, such as *Maersk Pelican*, *E-Ship 1*, and *Fehn Pollux*, which have fuels savings of 8.2%, 15% and 10 to 15% respectively (TP-1; TU-2; TU-3; TU-4; Enercon, 2013).

5 Discussion

In this section, the results of this thesis are discussed and compared with existing literature, to gain insight on the development and future of the FRIS, barriers to expansion of the technology and the importance of human factors in FR operation. Areas for further work are then explored and finally, aspects of this thesis are reflected upon.

5.1 Towards Sector Maturity

There is promising potential for innovation to continue in the years to come if the FRIS can become self-sustaining and FRs can become an established technology in shipping. As of yet, FRs have not reached commercialisation, that is to say that the technology has not moved into open competition in the incumbent regime as there has not yet been a FR installation which has not relied on subsidisation in some form (TP-1; TP-2). The development of the sector away from reliance on subsidisation requires the alignment of a number of variables, such as "fuel price, cost of technology, volume of installations at sea (to give confidence to the market), performance validation, regulations and favourable policies" (TP-2).

A major barrier for the sector is the misalignment of the technology's price and fuel costs. From a shipowner's perspective, the payback time is the most important factor for FR uptake, meaning fuel savings are always compared to overall fuel costs. Therefore, even if substantial fuel savings can be achieved, they are overlooked when viewed as a percentage of overall consumption (TP-1). This is the case on the *Viking Grace*, which has recorded fuel savings of 230 to 320 tonnes of LNG per year but only 1.5% when compared to the overall consumption (TP-1). The savings of this vessel are substantial, considering the very unfavourable route, but do not translate into an attractive payback time (TU-1). On the other hand, the *Maersk Pelican* is evidence that high fuel savings can be achieved on retrofits of large vessels. The vessel has a payback time which is "on the edge of being viable"(TU-3) with fuel savings of 8.2% at a 55-80% utilisation rate (amount of days at sea) and efforts are being made to reduce the payback time to an optimum period of 5 years (TU-3).

The costs of FRs vary between US$320,000 and $800,000, depending on their size, not including engineering works (de Boer, 2020; Tillig et al., 2020). Retrofit installations are usually more expensive because they require engineering work to provide space for the FR foundation by rearranging deck equipment (TU-1; TU-2; TU-3; PTU-1; PTU-3), while new builds produce a more favourable payback time because the FR foundation and electrical cabling are integrated into construction costs (TU-2). Furthermore, the design of *E-ship 1* shows that new builds can fully integrate FR systems into a vessel's power management system, increasing energy efficiency and reducing payback time (Enercon, 2013).

5.1.1 The role of policy

This thesis found that policies (F4) and regulation (F5) directly stimulating FR uptake remain non-existent but that anticipation of such policy has nonetheless driven innovation of FRs. Standalone subsidies have been mobilised (F6) which have funded installations and R&D and policies should now be implemented which artificially lower the price of FRs on a wide scale and provide shipowners with additional revenue streams that reflect GHG emissions reduction. These two policy approaches will ensure that payback times are lowered.

TPs and TUs anticipate regulation which economically rewards GHG emissions reduction in the mid- to long-term (PTU-3). This has encouraged shipowners to explore fuel reduction technologies, creating a niche market for decarbonisation technology. FRs have proven competitive against other decarbonisation technologies, outperforming other wind propulsion technologies, both in theory (Bentin et al., 2016; Lu & Ringsberg, 2019; Traut et al., 2014) and in practice (TU-2; TU-3; PTU-3; de Boer, 2020). Furthermore, FRs can be retrofitted onto existing vessels, unlike many decarbonisation technologies such as alternative fuels, hull designs and air lubrication (TP-1; Comer et al., 2019).

Access to financial resources (F6) has improved since 2013, with the creation of a number of funded R&D projects in wind propulsion and EU subsidies for standalone FR installations. For an increased rollout of installations in the near future, interviewees agreed that funding must increase and become more easily accessible (TP-1; TP-2; PTU-1). A possible funding instrument, the European Investment Bank (EIB) Green Shipping Financing Programme, aims to provide 750€ million of investments into existing technologies, with up to 50% of debt financing for new builds and up to 100% financing of green technology retrofits (Gaudet, 2016). The program is hoped to provide "frictionless access to [finance] for investing in energy saving technology onboard ships" (TP-2).

Shipowners and TPs interviewed expressed wide support for carbon pricing policies, such as the EU's Emissions Trading Scheme (ETS) expanding to incorporate shipping (TP-2; TU-3). As of yet, such a scheme remains elusive despite calls for shipping's inclusion in the ETS since 2010 (Cames et al., 2015). Carbon credits would provide FR TUs with an additional revenue stream to fuel savings, shortening the payback time. Furthermore, it could provide at least €3.6 billion in additional revenue for reinvestment in shipping decarbonisation with insignificant impacts on consumer goods prices (Transport and Environment, 2019).

The fuel price remains an unpredictable variable in shipowner's economic assessments, but it can be artificially increased by introducing a levy on bunker fuel (Tillig et al., 2020). The EU's shipping sector currently enjoys fuel tax exemptions amounting to an estimated €24 billion per year (Transport and Environment, 2019). Given the proven performance of FRs, their simple operation and their ability to be retrofitted, an increase in the fuel price would stimulate shipowners to install the devices en masse.

Policies such as facilitated access to finance, an ETS for shipping and a bunker fuel levy would be welcomed by all actors involved in the FRIS and would ween the sector off state handouts, increase uptake and drive down technology prices. Globally, access to finance for developing countries would be a progressive step towards decarbonisation and economic independence, especially in Least Developed Countries (LDCs) and Small Island Developing States (SIDS) who are fully dependent on sea transport but heavily over-reliant on imported fuel (IMO, 2020; Searcy, 2017).

5.1.2 Gaining institution acceptability

For the FRIS to develop further, it must gain recognition and acceptance from formal and informal institutions in the shipping industry. The combination of knowledge sharing activities, interest lobbying and reference projects has improved acceptability from shipowners, classification societies and regulators. Future efforts in technology performance validation and resistance of the incumbent regime could secure the long-term development of the FRIS while the development and demonstration of alternative FRs will expand the potential fleet of rotor ships.

Two dedicated wind propulsion conferences and at least four industry partnerships have been launched since 2014, creating greater opportunities for knowledge sharing (F3) and providing evidence that there is a demand for new knowledge in the FRIS. Conferences enable actor relationships to be forged or strengthened, while industry projects allow for detailed and collaborative knowledge transfer. Both mediums catalyse the diffusion of knowledge in and out of the FRIS and reach institutions such as the EU and IMO.

The development of a trade association, the IWSA is a positive sign towards sector maturity and increases the industry's power to lobby its interests (F7) and reach formal institutions. The IWSA has grown from only twelve members and partners in 2014 to over 120 in 2020 (Excell, 2020; IWSA, 2020a). Further developments could be to create an association specifically dedicated to FRs and coordinate lobbying targeted at national and international policy. The evidence of collective lobbying from actor groups found in this study shows a significant development compared to 2013, when there was no lobbying and legitimacy creation was scattered (Rojon & Dieperink, 2014).

As shown in the representation of the organisational network in Figure 4-1, there is evidence that the FRIS is split into two clusters: Cluster A, centred around the IWSA and Norsepower, and Cluster B, centred around Emden-Leer University. This split could be detrimental to knowledge diffusion (F3) and hinder innovation. The organisations in Cluster B should join the IWSA to connect to the larger group of actors and establish a formal association which could increase communication, learning and strengthen the resilience of the sector.

Attitudes to wind propulsion have improved in recent years; more shipowners are taking the technologies seriously and more TPs are appearing (Werner et al., 2020). Operational reference projects are very important in increasing shipowner confidence in FRs (TP-1; TP-2). However, the industry remains highly conservative and many actors are uncomfortable with the new technology (TU-3).

Validation of FR expectations (F4) is an increasingly important field in research to increase institution confidence in the technology. This will, and has been, the subject of recent R&D projects such as MariGreen and WASP (IWSA, 2020b) with further work needed to be undertaken to increase the reliability of performance data and enable comparison between different ship types (IWSA, 2020b; MariGreen, 2019b; Werner et al., 2020). The SeaCLEAN model, developed by Tillig & Ringsberg (2019), is one of the latest accurate prediction tools for wind assistance technology performance and has been validated for FRs by comparison with operational vessel data (Tillig et al., 2020).

Reported fuel savings must always be considered in the context of the vessel concerned, to ensure shipowner expectations are appropriate. A vessel's size determines the size of rotors it can accommodate, with larger rotors producing higher overall fuel savings (PTU-3). However, percentage savings present the fuel savings compared to overall fuel consumption (TP-1). Furthermore, vessels with high fuel consumption, such as the *Viking Grace* will produce lower percentage fuel savings than other, more fuel-efficient vessels, despite having substantially higher absolute fuel and GHG emissions savings (TP-1).

Therefore, analysis of fuel savings using percentages alone can result in misunderstandings of the technology (TP-1). Shipowners expecting fuel savings of up to 20% on high-speed, high consumption passenger vessels will be disappointed. On the other hand, owners of smaller vessels like to *Fehn Pollux* can reasonably expect about 15% for retrofits.

FRs do not pose too great a threat to the incumbent regime (F7) in the short term because they cannot replace traditional fuel altogether, being a means of auxiliary propulsion that reduces fuel consumption by under 20% (IMO, 2020). The extent to which incumbent companies actively resist increased alternative propulsion methods is unclear. Company norms which discourage long-term vessel retention may be justified to protect tanker safety but have the effect of discouraging the uptake of wind assistance technologies. In the future, if consumer confidence increases and advancements are made in wind propulsion, the technology could be legitimised as an alternative main propulsion system and incumbent resistance from traditional fuel interest groups could increase. In this scenario, associations such as the IWSA would be indispensable in providing counter-lobbying and counteracting resistance to change.

5.1.3 Reanalysing the interaction of functions

Considering the discussion of policies and institution acceptability in the FRIS, the interaction of functions in Section 4.1.2.8 can be reanalysed. The original linear model of interaction shown in Figure 4-3 is similar to the findings by Karslen et al., (2019), who show that policy for establishing demonstration projects increases shipowner expectations. However, there is a 'missing link' in the original linear interaction which is required to transform the model into a circular interaction, as expected following the method of Hekkert et al. (2007).

By reanalysing the fulfilment of each function, it is proposed that the missing link is F7, or creation of legitimacy, as shown in the circular model in Figure 5-1. This model takes the previous linear model and proposes that creation of legitimacy (F7) is caused by the guidance of the search (F4), producing actor groups that lobby institutions for resource mobilisation (F6), in turn creating more reference projects to increase learning by doing (F2) and feeding back through increased expectations (F4).

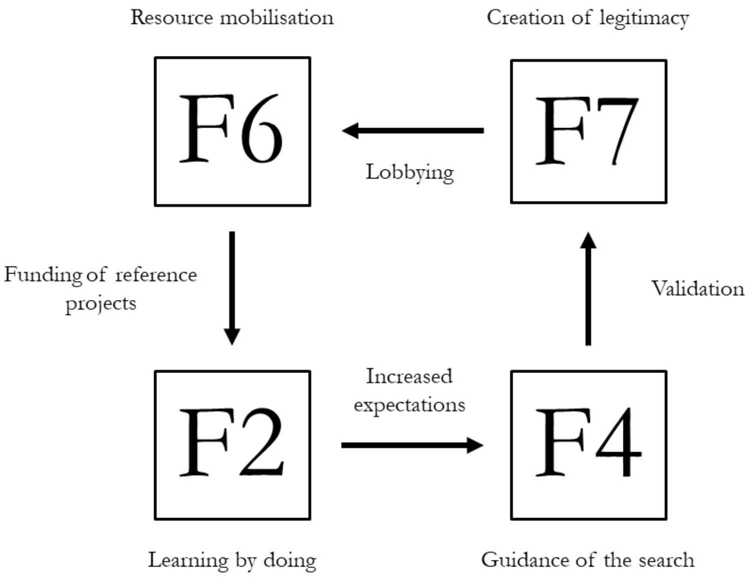

Figure 5-1 'A proposed circular function interaction in the Flettner rotor innovation system'. Source: Author's own work.

By comparing this interaction of functions with the typical motors of change described by (Hekkert et al., 2007), the model in Figure 5-1 most closely resembles Motor B. The models are similar, but Motor B includes entrepreneurial activities (F1) between F7 and F6. Since there is already an established network of new entrants and patents for different FR types, it seems F1 is not a core function in this interaction, though it may have been instrumental in its establishment.

The model of function interaction in Figure 5-1 is similar to the agent-based model of Karslen et al. (2019) in the scenario where an institutional demonstration project policy exists. The innovation dynamics of their study are modelled using twelve processes, some of which are approximately comparable to functions in the above model. Processes 8 and 9, shipowner updating of knowledge from experiments and interaction with demonstration projects respectively (Karslen et al., 2019), are similar to F2. This leads to Process 10, an update of technical risk by shipowners and, later, Process 12, updated shipowner expectations (Karslen et al., 2019).

A major difference in the innovation models of Hekkert et al. (2007) and Karslen et al. (2019) is the incorporation of economic factors, specifically fuel prices and technology cost in the context of FRs. Karslen et al. (2019) find that the uptake of FRs due to a demonstration project policy depends on a rising fuel price, unless combined with a carbon price of US$50/mt$CO_2$. Hekkert et al. (2007), however, do not explicitly include economic factors. FRIS sustainability would come about when resource mobilisation (F6) is no longer required because reference projects can be funded by shipowners' own resources. In this case, legitimacy creation (F7) can focus instead on maintaining a favourable policy network and protecting the FRIS from the resistance of the incumbent traditional propulsion interest groups.

5.2 Flettner Rotors in Operation

5.2.1 Technical barriers to expansion

This thesis builds on the general operational impacts of wind assistance technologies explored by Bordogna et al. (2020), Mander (2017), Rehmatulla et al. (2017) and Tillig & Ringsberg (2019), elaborating on effects which have been suggested to potentially limit the technology's expansion, such as heeling, drifting, visibility impairment, crew and passenger comfort, maintenance and inaccessibility of waterways. The latter impact is shown to be the only significant barrier, with small vessels (under 5,000 dwt) being affected most. The development and demonstration of alternative FRs is a mitigating solution. However, a new barrier to FR retrofit uptake is identified in this thesis: the limit of available onboard power for driving FR motor(s). Nonetheless, FR performance can be significant at 75% of maximum rpm. It must be emphasised that, despite these barriers, the number of vessels eligible for FR installations that would produce significant savings is very large (TP-2).

This study shows that heeling and drifting can be caused by FRs but the effect is not noticeable or problematic while at open-sea or in port. It can, however, be an issue for complex routes with multiple sharp turns and manoeuvres in narrow straits. This contextual nuance perhaps explains the discrepancy in findings between the studies of Bordogna et al. (2020) and Copuroglu & Pesman (2018). Heeling and drift are not expected to be major barriers to expansion because most routes are predominantly at open sea and the effects are reduced by reefing the rotor(s), as noted by Tillig et al. (2020). This thesis shows that even in complex routes, heeling and drifting can be mitigated with adequate rudder size and bow thruster power.

Impacts on crew and passenger comfort due to vibrations or noise caused by the FR is shown to be a non-issue and thus FRs are suited to operation on passenger vessels. Similarly, the impairment of bridge visibility caused on platform FR installations is found to be easily mitigated by installing additional radar on the bow. Furthermore, maintenance required for FRs is shown to be very low.

Inaccessibility of certain ports or waterways is mentioned by respondents as a limitation to the expansion of standard FRs in retrofit (TU-2; TU-3). At least one planned installation has been cancelled because the operational reach of the vessel would have been severely reduced (TU-2). Vessels under 5,000 dwt are especially affected unless they have relatively high bridge heights because they usually navigate through smaller waterways with low bridges and berth at smaller ports with low-hanging port infrastructure (TU-2). The retrofitted 4,500 dwt *Fehn Pollux* has a relatively tall bridge so the installation of a FR did not increase its air draught (TU-2). Respondents identified waterways in two regions which are particularly affected: the Mississippi Delta in the USA (TP-3) and Humber River area in the UK (TP-2).

The evolution and increased installation of alternative FR systems such as displaceable, foldable or lowerable FRs will increase the sector's reach across diverse ship types and functions. While four displaceable FRs are operated on the *MV Afros*, foldable and lowerable systems have yet to be operationally deployed and some shipowners are weary of the extra crew workload and deck space potentially required (PTU-3). Installations of these systems at sea would provide demonstrations and increase shipowner confidence, potentially filling an operational niche securing their uptake as the sector expands.

This study finds that an important technical barrier to retrofit is the amount excess power available to drive FR motor(s). This affects retrofit installations because about 30 to 70kW of power is required per rotor. The case of the *Fehn Pollux* shows that this can be mitigated by ensuring that the bow thruster and FR(s) are never operated simultaneously, with no evident impact on performance (TU-2). The retrofit of the 10-year old *Maersk Pelican* usually operates FRs at 75% of maximum rpm (120 rpm instead of 160) to mitigate generator overload and nonetheless reports verified fuel savings of 8.2% over a year (TU-3).

5.2.2 Recognition of human factors

This thesis has pioneered the application of human factors to FRs in academic literature. The findings reveal, firstly, the impacts of FRs on the existing crew's socio-technical system of daily operations and work tasks and, secondly, the significance of human factors in FR performance. Human factors are discussed here and improvements suggested to ensure that the crew are properly recognised, considered and incorporated into FR operation. General recommendations include maintaining healthy and reciprocal communication between bridge, TU and TP and including the crew in FR optimisation.

The establishment and maintaining of transparent communication improve all human factor issues. TPs already maintain contact with crews and incorporate crew knowledge into FR design and optimisation (TP-1; TU-3). TPs should recognise bridge and engine crew workload and not overburden them with additional tasks or communication. Adequate communication requires crew engagement and cooperation to enable them to voice their concerns to TUs and TPs, using tools such as an appraisal system, satisfaction surveys and face-to-face meetings on board or onshore (Anastasiou, 2017). The case of automated reefing on the *M/S Viking Grace* demonstrates that bridge crews should be properly informed before any changes to FR operations occur and their opinions heard and considered.

Optimisation of FR operation should include crew input and their interaction with the FR should be approached, itself, as a factor for optimisation. Technical optimisation requiring additional crew work, such as manual tests of FRs, should not overburden the crew or be requested while the crew is occupied with other tasks.

Shipowners should be aware of the engine crew's workload to ensure that crewing numbers are adequate. Due to the low amount of maintenance work required, it is unlikely that an additional crew member is required, but this can only be assured if training and motivation is adequate.

The crew's motivation and expectations can be managed during training, satisfaction surveys and meetings (Anastasiou, 2017). If a vessel crew is to become responsible for FR maintenance, an assessment of crew capacity should be undertaken beforehand to reveal whether there are enough personnel. The engine crew should receive the proper training required to enter the FR and climb inside the confined space, up to the motor, in line with IMO regulations and safety certifications (TP-3; TU-3).

5.2.3 Improving Performance

This study reveals that the ability of the bridge crew to effectively use a FR system to reduce fuel consumption is determined by controllable human factors such as quality of training provided, usability of the FR interface and crew motivation. Shipowners and TPs who recognise the sailing importance of these variables and invest in improving them early-on will be rewarded by higher fuel savings throughout the FR operation (TP-3).

The solutions to human factor issues described below are ready for implementation in the short term and can easily be retrofitted onto existing vessels or incorporated into future installations. It is easier to resolve any issues while the technology is immature and so should be attempted as soon as possible (Kirwan & Ainsworth, 1992). Measures such as improving training, the user interface and crew motivation require no new technology and should be relatively inexpensive to implement.

Shipowners and TPs should prioritise FR human factors before the new generation of technical decarbonisation solutions, such as route optimisation and FR-engine integration, are ready for implementation. Researchers of new generations technical solutions such as these should follow principles of human-centric design in order to ensure optimum performance of the technologies and protection of crew well-being (Costa, 2018).

5.2.3.1 Training

The crew's understanding of effective FR operation can be improved through instructions and training (TP-3). All TU bridge crews received instruction manuals for operation (TP-1; TP-2; TP-3; TU-1; TU-3; Enercon, 2013) but, as described below, the quality of training provided varied greatly depending on the TP.

Emden-Leer University, in collaboration with MariGreen partners, created a three to four-day training course for the Fehn Ship Management bridge crew, including theoretical instruction and a navigation simulator which demonstrated FR effects on manoeuvrability and ship stability (TP-3). The training also included instruction on how to sail for maximum fuel efficiency (TP-3). Feedback was positive because it built crew trust in the system and an understanding of the impacts on navigation (TP-3; TU-3).

On the other hand, TPs Norsepower and Enercon provide less training to bridge crews (TP-1; Enercon, 2013) and "Norsepower has no plans to increase training or provide sailing manuals" (TU-3). Norsepower provided specific training to the bridge crew lasting about half a day that consisted of an explanation of operations, a demonstration of the FR and a Q&A session (TU-3). According to Enercon, "no special crew […] training is required" (Enercon, 2013, p19). Feedback was positive for Norsepower's training; the *Maersk Pelican* crew found the FRs straightforward to use (TU-3). However, this crew uses the devices to speed up their vessel more often than reducing main engine speed (TU-3).

For future installations, Fehn Ship Management do not plan to use the same training regime because it is considered excessive for such a simple device (TU-3). Instead, manuals including troubleshooting are deemed adequate (TU-3). Shipowners are under pressure to keep training short so the crew can get back to work and so prioritise safety and familiarity over effective sailing (TP-3). This attitude may prove detrimental to fuel savings on future installations, or produce human error that could otherwise be avoided (Anastasiou, 2017).

Training of the bridge crew to increase FR fuel saving performance is a sound investment on the part of shipowners (TP-3). Sessions lasting about two to three days are recommended to ensure familiarity, safety and understanding of sailing are provided to the crew (TP-3). Existing TU bridge crews possess indispensable operational experience which could provide PTUs with trainers for their crew. The knowledge from crews, drawing on experiences operating FRs and knowledge of general fuel consumption reduction, should be incorporated into training in a bottom-up fashion, contrary to the standard top-down design of training manuals in new maritime energy efficiency technologies (Man et al., 2019).

Misuse of FRs should be avoided in all cases because lower-than-expected performance of reference projects could cause damage to stakeholder perception and shipowner confidence. It is therefore in the interest of TPs to ensure adequate instruction and training to protect the reputation of their products and the overall development of the FRIS.

5.2.3.2 User interface

Instruction via the user interface can aid or impede the crew's fuel saving ability (Man et al., 2019). Even if crews are well-instructed about the principles of fuel savings through FR usage, they may be impeded if the user interface is unsuitably designed. FR display panels can aid the bridge crew by clearly instructing fuel saving actions. If the user interface is not correctly designed, it risks being ignored or even switched off by the bridge crew in favour of traditional instruments and navigational ability (Man et al., 2019).

A suggestion from two pilots interviewed on the *M/S Viking Grace* is that FR power savings should be displayed as a percentage of main engine power, allowing simple conversion to vessel speed (TU-1). The existing display panel presents FR savings in kW, which is not of use to the bridge crew. According to the Captain of the *Viking Grace*, "it is not easy to decide by how much to power down the main engine" (TU-1).

The concept of sailing is not new, even on modern ships; pilots and captains are already familiar with wind impacts on vessel speed, especially on larger vessels (TU-1). TPs and TUs should therefore act to increase the usability of FR display and control panels to facilitate crew usage of FRs for fuel efficiency. A general recommendation from Man et al. (2019) is that user interfaces should display a wide variety of information, giving crew members better freedom to make decisions.

5.2.3.3 Motivation

Bridge crew motivation is another key factor influencing sailing (TP-3; PTU-1). It can be an issue for shipowners to motivate effective usage of FRs (TP-3) but there are a number of different solutions being attempted.

Researchers at Emden-Leer University found that the substantial training given to the crew of the *Fehn Pollux* increased their motivation to use the FR correctly (TP-3). A solution used by Maersk Tankers is a system of 'pool points' which rewards crews of vessels with good fuel efficiency performance with bonus pay, possibly providing an incentive for effective FR usage (TU-3). Anticipating that FR fuel saving performance to be greatly impacted by crew usage and attitudes, Scandlines uses a different, albeit presumably less effective solution; the PTU intends to increase crew engagement and enthusiasm by promoting 'natural competition', displaying and comparing fuel consumption for ships on the same route to motivate the crew to outperform each other (PTU-1). Finally, the user interface can be a tool to increase motivation by displaying fuel saving and cost saving values to the bridge crew (TP-3).

5.2.3.4 Technological solutions

The development of route optimisation and integration of the FR with vessel functions are technical solutions to improving FR performance and reducing crew workload. These remain in development and may be generally available to shipowners in the mid- to long-term.

Route optimisation is a navigational software tool with a high potential to increase vessel efficiency by combining meteorological data from various sources to create an optimal voyage plan, based on wind conditions, sea currents, safety and ship characteristics (TP-2; TU-3; MariGreen, 2019b). In relation to wind propulsion technologies, route optimisation can incorporate device performance into calculations to produce increased fuel savings (MariGreen, 2019b).

Many interviewees saw route optimisation as the next step for increasing FR performance (TP-2; TP-3; TU-2; TU-3) and at least two vessels are already equipped with it: *Fehn Pollux* and *E-Ship 1* (TU-2; Enercon, 2013). The tools produce route suggestions based on parameters such as 'least fuel', 'least time' and 'least cost' (TP-3; Enercon, 2013). Researchers at Emden-Leer University designed a route optimisation system which is compatible with standard navigational chart software on the bridge and is installed on the *Fehn Pollux* (TP-3; TU-2). The tool is automatic and requires no work on behalf of the crew and almost no instruction because they are already familiar with the software (TP-3). Unfortunately, it has been mostly unused because it requires a large amount of data storage space to function effectively (TU-2).

The development of route optimisation may be hindered by shipping contracts which greatly limit route flexibility and demand punctuality (TU-3). This is an institutional barrier to the growth of FR performance which can only be overcome by a change in contractor attitudes.

Another solution which completely removes sailing human factors from influencing performance is to fully integrate the FR into the engine propulsion system and automate propulsion. A distinction can be made between 'standalone automation' and 'propulsion automation'. The former is the current automation provided by all TPs and explained in Section 4.2.2.1, while the latter is a concept of automating the ratio between main engine power and FR thrust, to produce optimum fuel savings. At present, FR programming is not yet sophisticated enough for the complexity of integration (TU-1) but this may be a promising solution in the future (TU-3).

New builds are capable of integrating FRs into a vessel's power management system for increased energy efficiency, as demonstrated on *E-ship 1* (Enercon, 2013). Further innovation could see FRs integrated into the rudder and propellers to optimise impacts on manoeuvrability through automation, without impacting bridge crew navigation (Werner et al., 2020).

5.3 Towards Zero-emissions Shipping

The overarching goal of any maritime decarbonisation technology should ultimately be to facilitate a movement towards zero-emissions ships. To meet the IMO's 2050 targets, zero-emissions vessels must become operational by 2030 (RINA, 2019a). It is envisaged that this can be achieved with the integration of wind propulsion with other decarbonisation technologies such as hydrogen fuel, batteries, air lubrication, route and weather optimisation, and onshore power systems (Department for Transport, 2019; RINA, 2019a, 2019b; Werner et al., 2020; Zanetti, 2013) on vessels specifically-designed and operated to be unreliant on fossil fuels (RINA, 2019a; Werner et al., 2020).

A number of designs for commercial vessels which aim to be predominantly wind-propelled have recently been produced, such as the wPCC collaborative project for a car carrier design by Wallenius Marine, SSPA and KTH Royal Institute of Technology (Werner et al., 2020), the Vinskip wind hull design by Serje Lade and the VPLP RoRo concept (Excell, 2020).

Institutional attitudes towards alternative propulsion methods have improved in recent years (RINA, 2019a) but issues of shipowner unacceptability remain (TU-3). The classification society ClassNK has prepared guidelines for all wind assistance technologies which will be applicable to future primarily wind-propelled vessels (IWSA, 2020b). Shipowners are concerned that punctuality and reliability of operations could be impacted on ships primarily-propelled by wind (TU-3; Werner et al., 2020). These expectations could be overcome by integrating wind and alternative fuels and improving route optimisation.

It is, however, largely in the hands of policy makers as to whether the GHG emissions cuts required in shipping can be achieved (RINA, 2019a). As this thesis has shown, regulation favouring decarbonisation technology and facilitated access to finance for sustainable investments will be instrumental in achieving the IMO's emissions reductions targets. Due to the long lifetimes of vessels and their accompanying infrastructure, policies must be swift to reshape the sector within the next decade (Department for Transport, 2019; RINA, 2019a).

5.4 Reflections

5.4.1 Theoretical Frameworks

The practical study of human factors has become possible for FRs due to the development of the FRIS into a stage where numerous operational reference projects exist. Only in this context could an in-situ usability assessment be conducted, producing the wealth of insight required to answer Research Question 2 and 3. In this sense, the timing was fortunate because few wind propulsion technologies are at the stage to be assessed in this manner. While a human factors approach should ideally be conducted from the beginning of the design process (IEA, 2020), usability assessments during the early adoption phase of a technology are nonetheless valuable to test human factors in an uncontrolled setting (Kirwan & Ainsworth, 1992).

5.4.2 Methodological Limitations

The limitations of each data collection method were considered in advance and efforts made to minimise their effects, as explained in the following sub-headings.

5.4.2.1 Document analysis

Document analysis is limited by the perspectives and subjectivity of authors (Sovacool et al., 2018) and by potential inaccuracy due to the lack of peer-review processes. It was thus not relied on as the main source of data collection. Furthermore, the method was more useful in TIS data collection than human factors because very little documents contain the detail on usability required for a rich and holistic assessment of human interaction with new technology.

Language presented a potential limitation because some documents from companies in the FRIS were written in languages that the author did not speak. In this case, an adequate translation was found online or with the help of a native speaker. Another limitation was the sensitivity of internal company documents such as risk analyses by TPs. These were not available to the researcher, thus reducing the data obtainable.

5.4.2.2 Semi-structured interviews

Semi-structured interviews with sixteen expert practitioners provided the bulk of the data collection in this thesis. Interview saturation was considered accomplished for data relevant to the mapping of FRIS dynamics, technical aspects of vessel operations and secondary usability data. In these cases, the latter interviews produced increasingly repetitive results and fewer new findings.

Data concerning organisations and networks of the FRIS, however, did not reach saturation and thus the network displayed in Figure 4-1 and the organisations listed in Table 4-1 to Table 4-5 are not an exhaustive depiction of the FRIS, being directly reflective of respondent subjectivity. As mentioned in Section 1.5, these results are therefore approximate and are subject to respondent subjectivity. They nonetheless paint a comprehensive picture of many organisations, and interactions in the FRIS provide the reader with an important frame of reference for the data presentation and discussion throughout this thesis.

A potential linguistic limitation in interviews was identified in advance because the majority of respondents were non-native English speakers. A contingency plan was to seek translation from someone fluent in the language in question but this was not required because all respondents spoke English at the level required for data collection.

Some interviews were not recorded but documented in note form by request of the interviewee or due to practical reasons. This was mitigated by rereading and reviewing notes directly after each interview to check for unfinished or unclear material. Any parts that remained unclear were sent back to the interviewee by email for clarification, along with any desired follow-up questions.

A degree of interviewee perspective was lost in some instances due to corporate confidentiality. This was understandable and did little to affect the final results because personal opinion was not critical for mapping the FRIS and, for human factors, where personal opinions were required, confidentiality issues generally didn’t reduce the amount of data available to be included in this thesis.

Face-to-face data collection risked producing answers desirable to the interviewer because respondents may find themselves in a social context of amicability (Sovacool et al., 2018). This effect was reduced by beginning interviews with emphasis on easily-answered technical questions first and allowing more subjective opinions to be expressed naturally as the interview continued.

Finally, the wider situation of the 2020 COVID-19 Coronavirus pandemic in Europe impacted the data collection of this thesis from mid-March onwards. Fortunately, data collection was almost complete by that point, including the visit onboard the *M/S Viking Grace*. Nonetheless, the ability to ask respondents follow-up questions via email correspondence was severely reduced because practitioners were busy producing solutions to continue shipping operations in unpredictable circumstances.

5.4.2.3 Usability assessment and direct observation

Arranging to perform direct observation on board a vessel was vulnerable to observation bias. Participants may have reacted to being observed or recorded, producing artificially distorted outcomes (Kirwan & Ainsworth, 1992). It was therefore important that the researcher's presence was as non-intrusive as possible and that enough time was given for the data collection that participants became at ease with the situation (Kirwan & Ainsworth, 1992).

Access to vessel areas and authorisation for recording data somewhat limited the amount of data available for collection. Access to key vessel areas of FR operations was authorised if accompanied by a crew member at all times, which in this case was the ship's Safety Officer. Access to the bridge during port manoeuvres was, however, not authorised. Furthermore, the recording of images was not authorised on bridge, so information about the user interface was instead recorded in note form.

The length of the data collection depended on crew availability. The length of observation depended on the accompanying Safety Officer's availability, limiting the data collection period. Furthermore, data collection on the bridge had to be carried out during non-critical sections of the route. Due to the complexity of the Stockholm – Turku voyage, the Pilots were only available for interview for short periods of time, sometimes just minutes. Despite these limitations, the usability assessment including observation and interviews lasted 4.5 hours, after which point saturation of all accessible data was considered achieved.

When asking questions of "how often", such as "how often is maintenance required?" or "how often do you manually place the FR on idle mode?", the crew found it hard to respond or provide clear answers due to the variability in such occurrences and the busy schedules of daily crew life, making the frequency forgettable. This meant the extent of additional workload was usually expressed in qualitative terms such as "low" or "not that often", which is reflected in descriptions throughout the thesis.

5.4.3 Findings

The degree to which the findings of this thesis is generalisable is difficult to assess, which is why a qualitative approach was used for data collection. Many variables were produced in the results, indicating the conditions determining whether each finding applies. Thus, it is hoped that actors can themselves assess whether the findings apply to them by comparing the variables with the case of their own vessel(s). For example, a PTU can look at Table 4-6 and read that the variable determining FR impacts on cargo handling is ship type. If that shipowner is looking to install FRs on a RoRo vessel, they need not be concerned about cargo handling. If, on the other hand, they operate dry bulk carriers, they should explore a displaceable FR solution to mitigate any impact on operations.

In the findings on human factors and technical impacts of FRs on operations, there is, naturally, a bias towards findings from the Viking Line vessel *M/S Viking Grace* because of wealth of data collected from the usability assessment conducted onboard the vessel. This has produced a rich and deep qualitative depiction of the interaction of FRs with a vessel's STS on multiple levels. For example, the crew were able to provide insights on heeling impact due to a FR which was not perceived by other TUs interviewed and was conflicted in literature.

Furthermore, the *M/S Viking Grace* has the lowest fuel savings of any rotor ship currently in operation (1.5%). This presents a deviant case study because it is an outlier compared to other vessels operating FRs (Sovacool et al., 2018), suggesting, presumably, an unusually unfavourable series of interacting variables determining FR operation and performance onboard and increasing the importance of this study.

The locations of key actors in the innovation system and policy activity related to maritime decarbonisation result in a heavily Eurocentric scope. While this represents the area where data on operational FR activity can be most readily collected, it must be emphasised that FRs have deployed on global routes on three vessels so far, interacting with port authorities around the world and receiving certification internationally. Innovation activity is not limited to Europe; innovation hubs for wind assistance technologies exist across the world, for example in the East China Sea, the Tasman Sea and the Strait of Georgia, off Vancouver, Canada (IWSA, 2020a; Nelissen et al., 2016). For FRs to become a globally accepted form of wind propulsion, they must gain recognition and acceptability from important regions of maritime trade outside Europe, such as East Asia and the coasts of North America.

Furthermore, it is important to note that traditional sail propulsion remains a viable and zero-emission transport mode for cargo in developing countries, especially in regions such as the Arabian Sea, the coast of East Africa, the Indonesian Archipelago and the Caribbean Sea (IWSA, 2020a). The emphasis on new technologies should not overlook traditional means of low-carbon shipping and policies should reflect this. Carbon pricing, if enacted in national policies or worldwide through the IMO, would reward sail technologies with revenue streams, promoting increased uptake and increasing the resilience of LDCs and SIDS. The potential for FR uptake on larger vessels in developing countries could also produce significant economic and environmental benefits, as shown in the case of Fiji by Searcy (2017).

6 Conclusions and Recommendations

The web of organisations developing FR innovation is growing and increasing the creation and sharing knowledge due to a selection of providers offering diverse solutions (TPs) and first-mover shipowners (TUs) operating FRs on various ship types. The considerable fuel savings offered by the technology and the anticipation of regulation rewarding GHG emissions reduction attract shipowners, while the access to funding for installation enables uptake. Important activity to increase institutional acceptability and create a lobbying platform for wind propulsion technology have been made possible by the IWSA trade association and formal and informal public-private partnerships.

However, the sector remains reliant on state subsidisation and the current payback time length prevents widespread shipowner uptake. Furthermore, institutional discomfort and sector conservatism remain widespread due to uncertainty surrounding fuel savings expectations and the interaction of FRs with vessel operations.

Firstly, in order to address the payback time, this thesis identifies a selection of immediately available policies to stimulate widespread FR uptake. Facilitating access to investments in energy-saving technology for shipowners will reduce technology costs and uncertainty while removing tax bunker fuel exemptions and introducing tax exemptions for fuel-efficient vessels would artificially increase the price of fuel. Furthermore, the incorporation of shipping into the EU ETS would provide shipowners with an additional revenue stream from operating FRs.

Secondly, to increase institutional acceptability and reduce uncertainty, this thesis identifies the impacts of FRs on vessel operations, based on real-world experience. It is found that issues related to noise and vibrations, heeling and drifting, crew and passenger comfort and maintenance work are all have very little or negligible impact on vessel operations. However, inaccessibility to waterways and onboard power availability are demonstrated to be barriers to retrofitted FR uptake but can both be overcome using existing technical solutions and, despite these barriers, a very large number of vessels remain eligible for FR installations with significant resulting fuel savings.

Finally, this thesis adopts an original perspective in analysing FR research by applying the human factors theoretical framework to explore the interaction between the technology and crew members during operation. This reveals that human factors exist in FR operation and that fuel savings are directly dependent on the bridge crew's usage of, and attitudes towards, the technology. In operation, reciprocal and transparent communication between crews, shipowners and TPs is critical to ensuring bridge crew well-being is protected and engine crew workload should be monitored to ensure they are not overburdened. To improve FR performance, TPs and shipowners should introduce measures such as creating comprehensive educational training courses delivered by experienced crew members, enhancing user interfaces and motivating bridge crews to correctly use the technology.

A key objective of this thesis is to suggest solutions to develop FR innovation and improve the technology's integration into the existing socio-technical system. The findings produce clear and succinct recommendations, presented to four influential actor groups: policy makers, TPs, TUs PTUs. Overarching characteristics throughout these recommendations are the outstanding potential for informed policy to advance FR innovation and uptake, the need for organisations to recognise human factors in FR design, operation and performance and the need for communication and collaboration across actors and actor groups.

6.1 To Policy Makers

Policy makers should understand that a competing market of innovations has evolved because shipowners and TPs anticipate regulations that financially reward GHG emissions reduction. The time to implement such policies has arrived and FRs have been demonstrated to produce considerable reductions in fuel consumption. Policy makers should implement market-based instruments that lower payback times for shipowners and adjust the maritime regulatory landscape to facilitate the growth of FRs and other wind propulsion technologies.

Based on the informed opinions of expert practitioners and the findings in relevant literature, it is recommended that:

- The MEPC should follow the advice of Resolution 75(26) to create an IMO regulatory environment supportive of wind propulsion technologies;
- The EU should immediately incorporate the shipping sector into the ETS to provide shipowners with an additional revenue stream from FR operation;
- National and international institutions should create funding instruments to offer shipowners facilitated access to investments in GHG emission reduction technologies, similar to the proposed EIB Green Shipping Financing Programme;
- National and international institutions should cancel tax exemptions for bunker fuel, increasing the fuel price, improving the business case for FRs;
- National, municipal and port authorities worldwide should introduce voluntary certifications for vessels with reduced environmental impact to pay lower taxes or berthing fees, similar to the Green Award eco-label.

6.2 To Technology Providers

TPs should recognise that human factors influence FR operation and performance and understand that opportunities exist to improve the design and usability of their products. Furthermore, realise the mutual benefit of collaboration between actors in improving FR innovation. Accordingly, the subsequent recommendations should be followed:

- Concentrate on optimising human factors in FR operation and implementing human-centric design before pursuing technological solutions for optimisation;
- Establish and maintain transparent communication with the crew to improve all human factor issues, using tools such as an appraisal system, satisfaction surveys and face-to-face meetings;
- Develop a comprehensive training course lasting roughly two to three days that includes not only safety and familiarity with the technology, but also detailed sailing instructions for FR usage to reduce fuel consumption, an explanation of the user interface (including all alarms), an explanation of fuel savings calculations.
- Work with TUs to create bottom-up training courses for bridge crews operating FRs, based on crew knowledge and experience;
- Emphasise to customers that additional investment in training provides substantial returns in the form of increased fuel savings, shortening the FR payback;
- Design display panels to assist and motivate sailing. Displays should instruct bridge crews how much engine power can be reduced while maintaining service speed, according to the wind conditions. Power savings should be displayed as a percentage of

total power, instead of in kW, so that pilots and captains can convert the value into knots;
- Communicate with diverse actors, including shipowners, classification societies and research institutes, to share knowledge. Join relevant partnerships and industry associations to advance FR installations, R&D and publicity.

6.3 To Technology Users

Like TPs, TUs should recognise the influence of human factors in FR operation and performance. Furthermore, they should realise the value of their reference vessels and experienced crews to build FR knowledge and promote FRs, in line with the following recommendations:

- Work with TPs to create bottom-up training courses for bridge crews operating FRs, based on crew knowledge and experience which offer, if possible, TU crew members as trainers;
- Produce and implement motivation for bridge crews to use FRs to reduce fuel consumption, such as bonus pay rewards for high fuel efficiency and encouraging natural competition between vessel crews;
- Form partnerships with classification societies to inform regulations based on operational experience;
- Work with research institutes and other TUs to validate, compare and optimise FR performance data;
- Communicate with PTUs to share experience from reference projects;
- Join industry associations to advance FR installations, R&D and publicity.

6.4 To Potential Technology Users

PTUs should consider FRs as a reliable, proven and safe option to reduce fuel consumption, understanding the findings from shipowner and crew experience. The following recommendations should be contemplated:

- Be aware of FR impacts on vessel operations in technical (see Table 4-6 in Section 4.2.1) and human factor terms (see Section 4.2.2), recognising that impacts related to noise and vibrations, heeling and drifting, crew and passenger comfort and maintenance work are generally insignificant and manageable.
- Understand that the inaccessibility of certain waterways and limited power availability onboard are barriers to FR retrofits on some ships, but recognise the solutions available that mitigate these problems;
- Understand the technical and human factor variables influencing FR performance (see Table 4-7 in Section 4.2.3) to produce optimum performance and a shorter payback time;
- Invest in crew training for future installations to improve fuel saving performance, shortening the payback time;
- Consider the diverse types of FRs (see Figure 4-2 in Section 4.1.2.2) demonstrated to be able to fulfil shipowners' particular cargo handling and air draught requirements, such as passing under bridges and accessing overhead berths;

- Communicate with diverse actors, including other shipowners, TPs, classification societies and research institutes, to learn from reference projects. Join relevant partnerships and associations to advance FR installations, R&D and publicity.

6.5 Further Work

Throughout this thesis, the theoretical frameworks of TIS and human factors have been approached side-by-side, but consistently separately. A synthesis of the two theoretical frameworks could be attempted in the future, but was deemed outside the scope of this work. The synthesis could potentially evolve out of the marriage of knowledge sharing in IS theory and the findings from human factors research. The TIS dynamics of knowledge creation 'by doing' (F2) and knowledge diffusion through networks (F3) are relevant because, while knowledge and experience may advance through reference projects, diffusion of information relevant to vessels may be difficult to diffuse outside of that context. Thus, the integration of human factors into the context of the TIS can potentially reach a wider audience by producing findings relevant across multiple vessels.

As part of the interview questions, respondents were asked what academic research concerning FRs they would like to see published. Shipowners are interested in research into the costs of decarbonisation to aid their business case and reduce risks of investments. These studies should include analyses of the cost savings produced by imagined or existing FR operation. One TU respondent called for increased research into vessels primarily propelled by wind, specifically the potential compromises on vessel operations, such as punctuality expectations and risks to navigation.

Further research on fuel saving performance validation, optimisation and comparison can incorporate the variables identified in this thesis (see Table 4-7), and seek to quantify their effect. Human factors should be approached as an important influencer of performance and should be prioritised in optimisation work. One TP respondent commented that there is a growing availability of research validating actual fuel savings but that research into human factors has been lacking. Man et al. (2019) found that social boundaries between engine and bridge crew hindered communication between them, potentially negatively impacting measures for reducing fuel consumption. Further work could explore whether this factor has an influence on FR performance.

The possibility to quantify human factor impacts can also be explored, as well as the cost of implementing human factor solutions, such as improving training and developing motivational tools. This would provide shipowners with a business case for human factor enhancement.

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Appendix

An example of a pre-interview plan prepared for a technology user (TU) respondent, consisting of general and follow-up questions.

TU	**General questions**	**Follow-up questions**	**Rationale**
1	What motivated you to install Flettner rotors?	What motivates you to install wind assistance technology generally? Why choose Flettner rotors specifically, compared to other wind technologies?	I'm interested in understanding the reasons behind shipowners installing FRs. I'm trying to understand TU expectations and promises of TPs – do they match? What are their measures of success? Do these motivations have any impact on crew operations? E.g. low workload of FRs compared to other technologies?
2	How do crews react to the system?	Have they provided feedback? To whom? Is this feedback used to inform? If so, inform whom?	I want to investigate the crew's opinion of FRs and whether this opinion is perceived as valuable information to shipowners and TPs.
3	Are you still in communication with the TP?	If so, is it regular? How often? What information is shared? Where does the information come from? What is it used for? Is this information passed on to other TUs or PTUs? What is the service agreement for maintenance? Are there any activities or plans concerning FRs that you do independently?	I am interested in the communication between actor groups and what information is used for. I am interested in whether this information comes from the crew or not. I want to know whether development of FRs is always done in collaboration with TPs.
4	Are you in contact with any PTUs?	If so, is it regular? How often? In what capacity? Are crews involved in this communication? Are there any activities or plans concerning FRs that they do independently from the TP?	I want to understand the actor network and whether PTUs and TUs interact and communicate and how. I want to know whether development of FRs is always done in collaboration with TPs.
5	Were crew members involved in the preparations to operate FRs?	If so, since how early on were crew members involved? Where did they get information? Were crew from other TUs involved? What was the intention/expectation behind involving crew?	I want to know whether the crew members were part of the discussion about whether/how to operate FRs. I am interested where TU crew gained information about FRs and whether they collaborate with other TU crews.

6	Who is responsible for the rotor sail operation on board?	How many? If multiple crew members are responsible, how is this managed? Has the way it is managed changed? Will it change in the future? If so, why and how?	I want to see how the rotor sail interacts with the existing on-board crew organisation and ship management. I want to identify if this changes with ship type. I want to see whether there are any issues in integrating FRs into existing crew organisation.
7	In what ways do rotor sails affect work on board?	How does it affect specific tasks such as visibility, cargo/passenger handling, navigation, manoeuvrability, vibrations, interaction with port infrastructure, maintenance, etc. Where did you received this information? From crews or shipowners? Has there been an increase or decrease in work?	I want to know specific, technical, additional tasks that crew members have to conduct due to the operation of FRs. I want to know whether the crew themselves have provided this information or if it comes indirectly from shipowners. I want to identify if this changes with ship type. I want to know whether there is collaboration between TPs and TUs in managing workload and what lessons have been learnt. I want to understand whether the FRs mean more or less work for crew members and observe whether they are satisfied or under strain due to the new technology.
8	Is the rotor sail system automated?	If so, to what extent? What are the consequences of automation for the crew? How does it influence workload? Can crew manually operate the FRs if they please?	I want to know whether the automation of the system results in increased or decreased workload for the crew. I want to identify if this changes with ship type. I am interested in the power the crew have over operating the system.
9	Do rotor sails produce additional risks on board?	If so, what kind of risks? Have risks been reduced? How have they been managed? Are there plans to reduce risks in future?	I want to know the specific risks that might endanger crew members when operating a FR system and whether they have been or can be reduced. I want to identify if this changes with ship type. I want to know whether there is collaboration between TPs and TUs in managing risk and what lessons have been learnt.
10	Were crew members trained before using rotor sails?	If so, how? (certification, workshop, exam). Is training required before using the system? Are all crew trained? Who was trained? Is training continuous/ongoing? If so, how often and for how long? Will this training change in the future? Have you received feedback about training? If so, from who? Is training organised in collaboration	I'm interested in the amount of training that crew needs to operate FRs and how this training was conducted. I want to know how many hours of training crew might have to undertake and whether they are satisfied with the training. I want to know whether there is collaboration between TPs and TUs in organising and administering training and what lessons have been learnt.

		with TPs? Has this organisation changed? If so, why? Who is responsible for training?	
11	Do you plan to expand the FRs to other ships?	If so, what part does knowledge and experience of crews play in that expansion?	I want to understand the future of this industry and whether crew knowledge is important.
12	Is there anything else you think I should know?	Did I ask anything unexpected?	I want to identify unexplored areas to improve the next interviews.
13	Do you think the findings of this thesis will be useful for you and the industry in general?	What would you like to know that you feel hasn't been written about yet?	I want to know how relevant my research is for the field