ISBN 978-82-326-5405-5 (printed ver.)
ISBN 978-82-326-5729-2 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (electronic ver.)

NTNU
Norwegian University of
Science and Technology

Hans Tobias Slette

Doctoral theses at NTNU, 2023:42

NTNU

Doctoral thesis

NTNU
Norwegian University of
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Thesis for the degree of
Philosophiae Doctor
Faculty of Engineering
Department of Marine Technology

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Hans Tobias Slette

Vessel Operations in Exposed Aquaculture

Achieving safe and efficient operation of vessel fleets in fish farm systems experiencing challenging metocean conditions

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Doctoral theses at NTNU, 2023:42

PRINTED IN
NORWAY
NO - 1598

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

Printed by Skipnes Kommunikasjon AS

Abstract

This thesis investigates relations between vessel fleet configurations in fish farming, metocean conditions they operate in, and how well they perform. Marine aquaculture of Atlantic salmon involves various vessel operations that must be conducted as often as every day. Performing operations in rough metocean conditions can be challenging and entail elevated risk of accidents. Decisions on whether it is safe to initiate an operation is made by the captain, and there may exist company guidelines on operational limits, as decision support. A quantitative, applied research approach is used in this thesis to establish models and insight for correlations of interest. Field trips, interviews, data, and research literature supported the understanding of the behavior of a vessel fleet system, and what specific studies that were of greatest interest.

Three main topics are covered in the literature review: exposed aquaculture, vessels and fleets of vessels, and unwanted events. The first explores how exposure is understood in the setting of marine aquaculture and the state of the art for representation and analysis of marine weather. In addition, the effects of metocean conditions on fish, vessels and structures are covered, as well as the considerations when determining location of a new fish farm. Literature review on vessels starts by presenting methods on design of single vessels, with focus on capabilities. Thereafter, design of fleets is explored, in terms of fleet compositions. Finally, it introduces routing and scheduling of vessel fleets, given a range of constraints such as varying sailing speeds, capabilities, and operations requiring more than one vessel. The final section of the literature review covers relevant types of unwanted events, and how to prepare for and deal with them using support vessel as response resources. Research gaps were identified in the areas of understanding and considering availability for vessel operations in site selection, routing and scheduling of aquaculture support vessels, the effect of weather on aquaculture support vessel operations, and the evaluation of the emergency response capabilities of aquaculture support vessels.

Responding to the gaps, the thesis resulted in the following contributions to the literature: **C1** Framework for assessing the suitability of service vessels in a network of fish farms. **C2** Insight on the effects of the weather in a network of fish farms on service vessel fleet efficiency. **C3** Solution methods for routing and scheduling of service vessels. **C4** Methods for evaluating the performance of a fleet in a scenario. **C5** Method for assessing fish welfare emergency response capabilities and capacities.

The conclusion is that improved insight on the relations between vessel fleet, metocean conditions and performance was achieved, and that the presented methods and models enable generating further insight on these relations. New methods were applied in aquaculture, and this is the first comprehensive study of aquaculture vessels regarded as a fleet. Implications include enabling better safety both during vessel operations and with respect to emergency preparedness, and improved utilization and efficiency of support vessels, through increased availability. Recommendations for further work include further development of methods to improve validity and engage in introducing and implementing them in the industry to realize potential commercial benefits.

Sammendrag

Denne avhandlingen undersøker forholdet mellom sammensetninger av flåter med fartøy, værforholdene de opererer i, og hvor godt de yter. Sjøbasert oppdrett av atlantisk laks involverer flere ulike fartøysoperasjoner, hvorav noen må utføres så ofte som daglig. Om de gjennomføres i krevende værforhold kan det føre til lavere kvalitet på det utførte arbeidet eller gi økt risiko for ulykker. Beslutningen om en operasjon skal gjennomføres eller ikke blir tatt av kapteinen, ofte støttet av bedriftens retningslinjer for hvilke værforhold som aksepteres. En kvantitativ, anvendt tilnærming ble benyttet i forskningsarbeidet for å etablere modeller og innsikt om korrelasjoner av interesse. Feltturer, intervjuer, sensor-data og forskningslitteratur ble brukt for å danne en forståelse av oppførselen til fartøysflåte-systemet, og hvilke konkrete studier som var av størst interesse å gjennomføre.

Tre hovedtema ble dekket i litteraturstudien; eksponert havbruk, fartøy, og uønskede hendelser. Eksponert havbruk tok for seg hvordan eksponering er forstått i sammenheng med oppdrett i sjø og hvilke metoder som finnes for å beskrive og analysere marint vær. Det ble også gjennomgått hvordan værforhold påvirker fisk, fartøy og konstruksjoner, i tillegg til vurderinger som gjøres ved valg av lokalitet for et nytt oppdrettsanlegg. Delen av litteraturstudien som dekket fartøy inkluderte metoder for design av enkeltfartøy, med fokus på funksjonene og kapasitetene til fartøy. Deretter ble flåtesammensetning og ruteplanlegging belyst, for en flåte med fartøy hvor det er en rekke restriksjoner for oppførselen. Dette kan for eksempel dekke seilehastigheter, funksjoner og kapasiteter, og om operasjoner krever mer enn ett fartøy. Uønskede hendelser inkluderer kriser og annonsering av uventede behov. Den siste delen av litteraturstudien dekker relevante typer uønskede hendelser, fra personskader på mannskapet til algeoppblomstring, og hvordan havbruksfartøy kan inngå i kriseberedskap og kriserespons. Forskningshull ble identifisert innen det å forstå og ta hensyn til tilgjengelighet for fartøysoperasjoner ved valg av oppdrettslokaliteter, ruteplanlegging for havbruksfartøy, effekter fra værforhold på ytelsen til en flåte med havbruksfartøy, og evaluering av beredskapsressursen havbruksfartøy utgjør.

Som svar på hullene resulterte forskningsprosjektet i følgende bidrag til litteraturen: **C1** Rammeverk for å evaluere hvor egnet et havbruksfartøy er til å betjene et nettverk med oppdrettsanlegg. **C2** Innsikt om hvordan værforhold i et nettverk med oppdrettsanlegg påvirker effektiviteten til en flåte med havbruksfartøy. **C3** Løsningsmetode for ruteplanlegging for havbruksfartøy. **C4** Metode for å evaluere ytelsen til en flåte med havbruksfartøy i et scenario. **C5** Metode for vurdering av kriseberedskapen for fiskevelferdskriser.

Konklusjonen er at dette forskningsprosjektet har gitt økt innsikt om forholdet mellom flåte, værforhold og ytelse, og metoder og modeller for å frembringe ytterligere innsikt om disse forholdene. Nye metoder ble anvendt innen oppdrett, og dette er det første omfattende studiet på ytelsen til havbruksfartøy som en flåte. Betydningen av arbeidet finnes i at disse bidragene muliggjør bedre sikkerhet både for fartøysoperasjoner og kriserespons, i tillegg til redusert kostnadsnivå og forbedret effektivitet for havbruksfartøy. Anbefalinger for videre arbeid inkluderer videre utvikling av metodene for forbedring av validitet og involvering i arbeid med å introdusere og implementere dem hos næringsaktører for å realisere potensialet for kommersiell nytte.

Preface

This thesis is submitted for the partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD) in Marine Technology at the Norwegian University of Science and Technology (NTNU).

The work was carried out between August 2018 and October 2022, at the department of Marine Technology at NTNU in Trondheim, Norway. The main supervisor was Professor Bjørn Egil Asbjørnslett, with Professor Pål Furset Lader, Professor Kjetil Fagerholt and Professor Stein Ove Erikstad as co-supervisors.

The research was funded by the Norwegian Research Council through the Centre for Research-Based Innovation on exposed aquaculture operations, SFI EXPOSED. Grant number 237790.

Consequences of the covid-19 pandemic on society did affect the research project for two full years, from spring 2020 to spring 2022. Fewer field trips than planned were performed, due to fear of personnel being infected and quarantined, and access to industry and attendance at conferences was reduced.

Acknowledgements

There are many I would like to direct my gratitude towards, now that I finally deliver this thesis. This journey would not have been the same without your help and guidance.

First, I would like to thank my main supervisor Professor Bjørn Egil Asbjørnslett for giving me this opportunity, and for excellent support throughout these four years. Thank you for always being available when I needed advice. I would also like to thank my co-supervisors Professor Pål Furset Lader, Professor Kjetil Fagerholt and Professor Stein Ove Erikstad for their contributions. I am grateful that I got the opportunity to have all four of you as supervisors – your fields of expertise complemented each other perfectly for my phd work.

I’ve had the pleasure of sharing office, first with Sigurd Solheim Pettersen, then with Astrid Vamråk Solheim. I really enjoyed your company and the interesting discussions we had. Other colleagues I would like to mention both for their professional guidance and the social aspect are Farid Khazaeli Moghadam, Muhammad Mukhlas, and Endre Sandvik. To the many professors, PhD students, Postdocs and others I have had the joy of getting to know at the department; thank you, and I wish you all the best.

The research center SFI EXPOSED lead by SINTEF Ocean and Hans Vanhauwaert Bjelland has been an important facilitator for much of my research. This includes access to industry, researchers, and data. I also feel the need to thank SINTEF Ocean, as my current employer, and Jan Tore Fagertun in particular, for showing understanding in the finalization of the thesis.

I was lucky enough to perform a few field trips before covid came and closed everything down. A special thanks to FSV Group and the crew onboard MS Multi Safety, MOWI and the personnel at MOWI Valøyan, and Frøy and the crew onboard Gåsø Jarl.

Finally, I would like to thank my friends for willingly participating in discussions on subjects of my thesis, and my family for supporting and motivating me.

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Has been submitted to scientific journal

List of abbreviations

ALNS – Adaptive Large Neighborhood Search

CMA – Conditional Modelling Approach

COG – Center of Gravity

DERV – Dedicated Emergency Response Vessel

DES – Discrete Event Simulation

DP – Dynamic Positioning

ERRV – Emergency Response and Rescue Vessel

ERS – Emergency Response System

FEF – Fleet Efficiency Factor

GA – General Arrangement

GIS – Geographical Information System

GT – Gross Tonnage

HAB – Harmful Algal Bloom

IMR – Inspection, Maintenance and Repair

IMU – Inertial Measurement Unit

IRP – Inventory Routing Problem

ISA – Infectious Salmon Anemia

JPM – Joint Probability Model

LOA – Length Over All

MAB – Maximal Allowed Biomass

MFSMP – Maritime Fleet Size and Mix Problem

MILP – Mixed Integer Linear Programming

MSI – Motion Sickness Incidence

O&G – Oil and Gas

O&M – Operations and Maintenance

PD – Pancreas Disease

PSO – Particle Swarm Optimization

RAO – Response Amplitude Operator

SAR – Search and Rescue

SMCE – Spatial Multi-Criteria Evaluation

SVPP – Supply Vessel Planning Problem

S&B – Stun and bleed

TRL – Technology Readiness Level

TSP – Traveling Salesman Problem

VRP – Vehicle Routing Problem

VSS – Value of Stochastic Solution

W2W – Walk to Work

1 Introduction

1.1 Marine aquaculture of Atlantic salmon

Marine aquaculture of Atlantic salmon is a significant industry in several countries, including Norway and Chile (Iversen et al., 2020; Poblete et al., 2019; Tacon, 2020). Fish are typically hatched on land and grow in tanks containing either fresh or brackish water until they have reached the weight requested by the customer. Then they are transported out to sea-based, floating net pens for the grow-out phase. After approximately 12-18 months in pens, the fish have reached desired weight and are collected by a vessel before being harvested. Throughout this thesis the term “fish farming” is used to mean marine aquaculture of Atlantic salmon, and “fish” is used to describe groups of fish, for example, the group of fish in a pen. If the term is used to describe a single fish, this will be especially noted.

During the grow-out phase in the sea, fish are exposed to the surrounding environment and growth rate is affected by environmental conditions such as water temperature, oxygen saturation, and nutrient levels. Disease, harmful algal blooms (HAB) and sea lice are examples of possible, negative external effects on fish in open net pens. Also, fish farms affect the surrounding environment, for instance, through spilled feed, fish faeces, fish escapes and, they can possibly even affect each other as amplifiers of sea lice pressure.

Rules and regulations vary between countries, but they often govern aspects of fish welfare and how fish farming affects the surroundings. Restrictions on the cleaning of nets at sea is an example of how the effects of fish farming on the environment can be reduced (DNV, 2021; Floerl et al., 2016). In Norway, fish farms are required to fallow for a period between two generations of fish to reduce total load on the environment, transmission of infection from one generation to the next, and lice pressure (Akvabiosikkerhetsforskriften, 2022; Forskrift om lakselusbekjempelse, 2012; Meld. St. 16 (2014-2015)). There are also regulations both on the acceptable number of lice per fish in a net pen, and relations between lice pressure in an area over time and allowed biomass production in the area the following year (Produksjonsområdeforskriften, 2017).

A typical fish farm in Norway has a maximum allowable biomass (MAB) of 3000 to 7000 tons, given by the license to operate. These fish farms are usually made up of 6 to 12 flexible net pens. Several design variations exist; however, most flexible net pens consist of a flexible net suspended from a circular, flexible, floating plastic tube – called the floating collar - with a system of ropes and weights maintaining the shape. Figure 1 shows a common pen design, a cylindrical net pen with a bottom ring. Net pens are moored to a frame structure of ropes at around 10m depth, which is held in place by buoys and anchors. Net pen size varies, and the circumference is typically between 120m and 180m, with depths usually ranging from 15m to 30m. The large size of some aquaculture support vessels affects the layout of net pens in some fish farms, for instance, by having empty routes in the mooring frame so that there is more room for vessels to maneuver. This is illustrated in Figure 2.

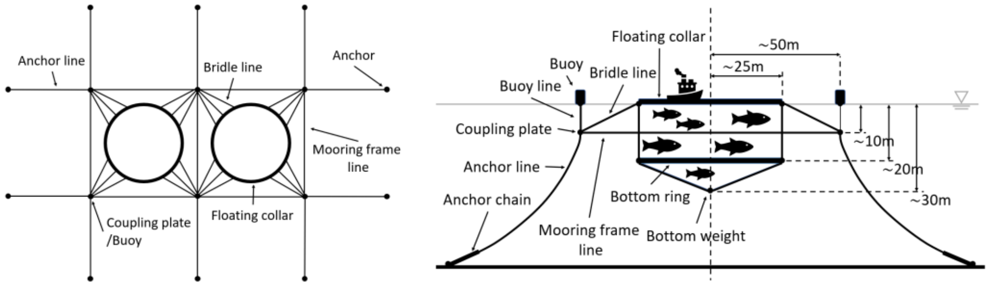

Figure 1. Top view of a fish farm with two net pens, and side view of a single net pen of typical dimensions. Names of components are included. Inspired by Shen et al. (2018).

1.1.1 Operations at fish farms

Operating a fish farm requires operations that can be classified into four groups: Handling of fish, construction and maintenance of structures, feeding, and maintaining a good environment for the fish. *Handling of fish* covers transporting fish to and from the fish farm, sorting, delousing, treating diseases, and harvesting the fish. *Construction and maintenance of structures* includes building the fish farm, inspecting, and maintaining the structural health of components, and repairs such as fixing holes in the net or damages after a storm. *Feeding* the fish is the most frequent operation and is usually performed by delivering feed pellets to the pen through a tube from the feed barge. Feed is delivered to the feed barge either in bags or bulk from a feed carrier. *Maintaining a good environment for the fish* includes common operations such as cleaning of net to maintain good water flow through the pen, removal of dead fish, and rarer operations such as protecting fish from predators or oil spills.

Operations are motivated by production efficiency, production quality including fish welfare concerns, and compliance with rules and regulations (Akvakulturloven, 2005; Mattilsynet, 2022). Soon aquaculture will be included in the European Union (EU) taxonomy for sustainable activities (The Aquaculture Advisory Council, 2021). This is likely to drive interest for improved insight on vessel fleet operation both through the potential for reduced greenhouse gas emissions, and the role of vessels in ensuring good fish welfare throughout the production cycle.

Aquaculture support vessels are involved in most operations at fish farms, from transporting crew to pens, to delivering fish for harvest. Aquaculture support vessels can be divided into three main categories: fish handlers, feed carriers, and service vessels. It should, however, be noted that there is overlap between the categories in terms of the capabilities of the vessels, which means that capabilities mainly associated with a group is not exclusive to the group. Also, some vessels are difficult to place in just one category.

Fish handlers covers well-boats, stun & bleed(S&B) vessels, processing vessels, ensilage vessels, and barges used for delousing and sorting. They vary in size and are often between 40 and 90 meters in length, with the barges typically being a bit smaller. Well-boats transport live fish in tanks of water called wells, and they often have additional capabilities such as sorting and different delousing methods. S&B vessels are used in harvest, stunning and bleeding the fish before transporting the fish to processing facilities on land. Fish is stored in Refrigerated Sea Water (RSW) systems on board. Processing vessels go one step further than S&B vessels and are capable of slaughtering fish. Dead fish that is removed from the pens during the grow-out phase becomes ensilage and is transported from the fish farm using ensilage vessels. Barges are low-cost solutions for performing some of the same operations as well-boats, most notably mechanical delousing.

Feed carriers transport feed to the fish farms and are close to well-boats in size. Large amounts of feed are consumed every day, and feed carriers sail roundtrips from a loading port visiting up to several fish farms in one trip. It is crucial for fish farms that they do not run out of feed. Having no interaction with fish, operation of feed carriers resembles that of normal short-sea shipping (Hartvigsen, 2019; Haugland & Thygesen, 2017). However, positioning of feed barges in between skerries can make it challenging to safely maneuver the vessels to the barges. Many vessels have dynamic positioning keeping them at a fixed position close to, but disconnected from, the barge during delivery. Feed is either delivered in bulk or bags.

The service vessel category covers all other vessels used in fish farming: Small open speed boats, location vessels, service vessels, diver support vessels, and others. Small open speed boats are used to transport personnel quickly between pens and the feed barge at a fish farm. Location vessels refer to workboats of a length of around 8-12 meters with a work deck and usually a small crane and some other basic equipment. These perform simple operations such as inspection of fish and are used to support other operations including changing of net or well-boat operations. Both the small speed boats and location vessels are usually dedicated to one fish farm but may briefly support other fish farms in their vicinity. Service vessels have more equipment enabling them to perform more operations, and with usual lengths of 15-40 meters they also have higher capacities than location vessels. Typical operations include mooring operations, construction, and transportation of larger items such as nets. Diver support vessels are fast boats with a length of around 12-15 meters that primarily performs diver operations. The group “others” includes, for example, crew transport vessels or manager vessels. It should be noted that the term “aquaculture service vessels” is often used to cover what we here refer to as location vessels and workboats. Simple illustrations of the most common vessel types are shown in Figure 2.

Vessel operations are dependent on metocean conditions and are performed only if the crew is confident about the quality of the operation, for instance, in terms of fish welfare and safety. Metocean conditions affect motions of vessel and fish farm which can entail challenging working conditions in harsh weather. Further, the fish is directly affected by metocean conditions meaning that their tolerance for stress and handling can be reduced. Availability for vessel operations varies between fish farms and is a result of the exposure to weather at the location. Figure 2 shows exposure in terms of fetch length for a fish farm in mid-Norway. Fetch length is the distance of open water over which waves can build up if the wind blows from that direction. There is no standard definition for how to determine the exposure of a fish farm, however, it is a result of, among other factors, the island geography, seabed topography, and climate of the location.

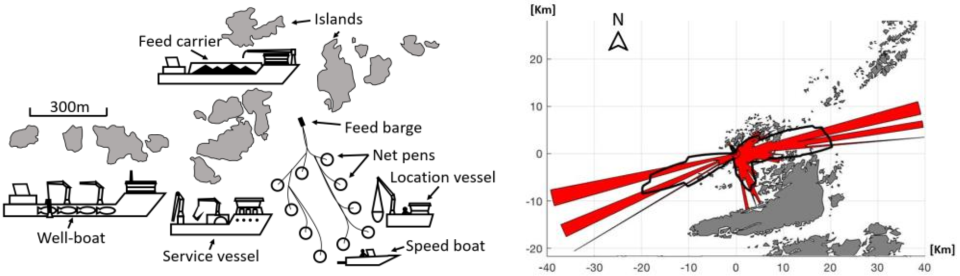

Figure 2. Illustrations of vessel types are overlaid a map of a fish farm and surrounding islands. Islands, feed barge and net pens are to scale, while the vessels are not to scale. The right part of the figure shows fetch length of the location in the different directions.

Design and engineering of vessels and fish farm structures is covered by several regulations ensuring appropriate risk assessments and safety for personnel, structures, and escape of fish (Forskrift om bygging mv. av mindre lasteskip, 2015; NYTEK-forskriften, 2011; NYTEK23, 2022; Standards Norway, 2021). Health, safety and environment (HSE) onboard the support vessels is regulated in, among others, Akvakulturloven (2005), Internkontrollforskriften (1996), and Arbeidsmiljøloven (2005). However, it should be noted that, in Norway, being a fish farmer is the second most dangerous profession in terms of occupational injuries (Holen et al., 2018a). Probable causes include a lack of understanding of risks, and a pressure to prioritize the completion of operations (Holmen, Utne, et al., 2017; Kongsvik et al., 2018).

1.1.2 Set of locations, fleet of vessels, and zones

Consolidation and economies of scale is prominent in fish farming, as it is in other industries. Large fish farming companies organize fish farms so that these benefits can be achieved. This means having several fish farms in geographical proximity to each other and to coordinate operations between fish farms. Some of the most notable benefits are related to distance from and utilization of onshore infrastructure such as smolt facilities and slaughterhouses, transportation logistics, and support vessels. Production cycles at fish farms are determined according to a central harvesting plan. Fish farmers control a fleet of vessels that are distributed to the fish farms based on reported needs for operations. It can consist of both vessels owned by the fish farmer and chartered vessels from a shipping company. Movement of vessels between fish farms and across production areas or disease control zones are governed by regulations (Akvabiosikkerhetsforskriften, 2022; Karlsen et al., 2021; Produksjonsområdeforskriften, 2017). This can include requirements related to when vessel cross borders of disease control zones, such as disinfecting the vessel, controls, and quarantine. These cost both time and money, constituting a barrier for cooperation across these borders. However, large companies do share vessel resources across several zones. This means that, at any given time, each vessel has a status with respect to requested operations in terms of what preparations it must perform, and how far it must sail to serve the request. Figure 3 shows fish farms owned by a large fish farming company within a production area and illustrates positions of support vessels.

Fish farms have different sizes, technology, and exposure. Most fish farms are placed in sheltered areas, while there is a trend of expansion into more exposed areas (DNV, 2021). The main driver of the expansion is need for space, as areas close to land are becoming increasingly crowded and authorities limit allocation of production licenses in production areas based on sea lice pressure (Hersoug & Johnsen, 2012; Produksjonsområdeforskriften, 2017). Norwegian authorities have set an ambitious goal of a five-fold increase in total production from the 2010 level by 2050 (Meld. St. 22 (2012-2013)). A solution is to move further out, into more exposed areas where there are fewer fish farms, or even into open ocean outside the production areas. DNV forecasts that 13% of finfish marine aquaculture will be offshore in 2050, and that the majority of these investments will be made before 2030 (DNV, 2021). In Norway this expansion is partly driven by subsidies through the allocation of licenses to a selected group of novel fish farm concepts that "require significant innovation and significant investments" (Norwegian Directorate of Fisheries, 2021b). It was not required that the concepts are related to exposed fish farming, but several are, including the concepts that have received the license allocations with the highest allowed biomass and have come the furthest in the realization of the projects (Norwegian Directorate of Fisheries, 2021a). Examples include large steel structures like Ocean Farm 1 and Havfarmen (Ocean Farming, 2019; Robertsen et al., 2021). The Norwegian government is currently developing a license regime for open ocean fish farming, and has proposed three areas to consider in the first round of allocations (Norwegian Directorate of Fisheries, 2022). China and Latin America are predicted to accompany Europe and Norway in being the biggest players in offshore finfish production in 2050, with the accumulated total reaching 4 megatons (DNV, 2021).

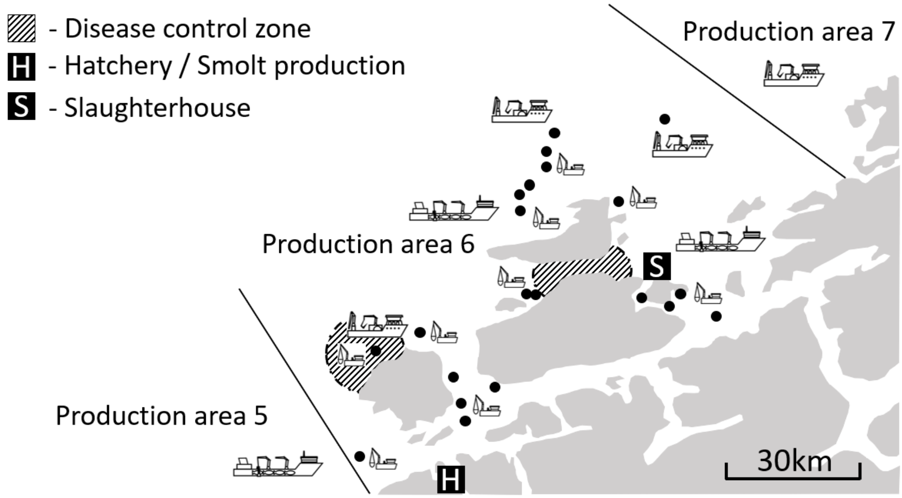

Figure 3. Example overview of production areas, disease control zones, and positions of fish farms, support vessels, and onshore infrastructure controlled by a company.

1.2 Research project

In 2015, SFI EXPOSED – the Centre for research-based Innovation on exposed aquaculture operations, was established as an eight-year innovation hub comprising stakeholders from the aquaculture industry, research and academia (SFI EXPOSED, 2015). The center covers four research areas related to technological innovations: Autonomous Systems, Monitoring and Decision Support, Structures, and Vessel Design. In addition, there is research area 5 – Safety and research area 6 – Fish Welfare. Industry partners from fish farmers to suppliers of infrastructure and technical solutions are engaged in the research.

This thesis is part of research area 4 of SFI EXPOSED – Vessel design for exposed operations. The research area has a stated goal: “Design vessels, on-board equipment and logistical solutions that enable safe and efficient operations in exposed areas”, and four research tasks were identified within research area 4. The following research tasks are translations from Norwegian in SFI EXPOSED (2015):

> **Vessel design and sea-keeping capabilities**: Study and develop new designs for all three types of vessels with the sea-keeping, structure interaction and equipment required for operations at exposed locations.
> **Vessel and structures coupling**: Integrate simulation models and software

> tools to analyze the different floating objects and to account for hydrodynamic coupling effects between vessels and structures.
> **Analysis of operations**: Develop simulation scenarios for exposed aquaculture which allows simulation of critical operations. Simulations are a tool to evaluate the goodness of fit for the proposed vessel designs and may be used as a feedback loop in the design process.
> **Logistics optimization**: New logistics solutions need to cope with the changes in vessels and fleet operations. Important issues to consider are onshore and offshore storage, personnel and equipment logistics.

The research tasks of research area 4 are related to this thesis as illustrated in Figure 4. Logistics optimization and analysis of operations is the main focus, while the two other tasks are covered to a lesser extent, as is indicated by the dotted lines. However, vessel design, seakeeping and vessel-structures coupling, affects operations and logistics which means that this is a joint problem where all aspects need to be considered.

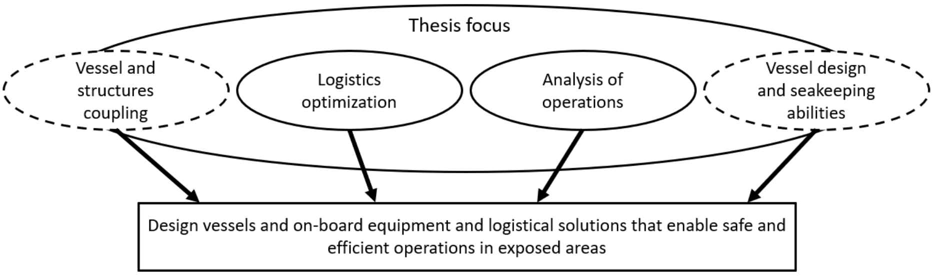

Figure 4. Goal and research tasks of research area 4 in SFI EXPOSED, in relation to the scope of the thesis. Logistics optimization and Analysis of operations constitute the main focus. However, formulation of the research problem of the thesis is given in section 1.1.

1.3 Research problem

The research problem of the thesis is based on descriptions of research area 4 of SFI EXPOSED, as illustrated in Figure 4. A research question is formulated, with the goal of the thesis being to answer this question. A set of research objectives describe necessary tasks to be completed in order to achieve this.

Based on the given background, this thesis seeks to understand the challenges that arise for vessel operations at exposed locations, and how safety, efficiency, and fish welfare can be maintained. Availability for operations is a necessity for efficiency and ability to perform operations required to maintain good fish welfare. Thus, the research question of this thesis is:

> *"How can design of and operations planning for aquaculture support vessels provide available and safe vessel operations at exposed fish farms?"*

It all starts with each individual vessel's ability to perform an operation at a fish farm. Functional requirements must be achieved, that is, the vessel must have the right equipment and sufficient capacity. In addition, there is the contextual and temporal aspects of the task, that is, if it can be executed at that location and under the current metocean conditions. Availability and operability are terms related to a vessel's ability to perform operations with respect to metocean conditions and operational limits. A vessel has an operability in a given context which is a result of its operational limits and metocean conditions. Higher operational limits give higher operability. Availability is the corresponding property of a fish farm, describing to what degree weather hinders support vessels in serving the fish farm, for example resulting in delays of operations. Tolerances of vessels should therefore be suited to metocean conditions at locations – which in turn means that operating conditions should be considered when acquiring vessels to serve fish farms. Adhering to operational limits is related to safety both for personnel and fish. Uncertainty in weather conditions can entail that vessels encounter situations where they have arrived at a fish farm ready to work, but the metocean conditions are rougher than anticipated and exceed operational limits. Sometimes, the captain decides to go forward with the operation. Having vessels that are better suited to the locations, and thus more seldom encounter such situations, is a benefit for safety. Service demands at fish farms are stochastic and this entails variability in load and can result in peaks that are significantly higher than the average. In addition, it can affect the availability of the vessel if request frequencies for various operations change, and operations have different operational limits.

For vessels that serve more than one fish farm, metocean conditions and interface between fish farm and vessel should be assessed for each fish farm. When considering a network of fish farms, an interesting question is if it is possible to exploit differences in simultaneous weather between fish farms when routing service vessels so that there are benefits related to considering the fish farms as a network rather than individual fish farms. In such a network, where fish farms have different exposure levels, experiencing weather exposure from different directions, or some are more sheltered than others, it is likely that the operating conditions at the same point in time are acceptable at some while unacceptable at others.

Since fish farms are served by several vessels it is the availability and safety for the fleet as a whole that is the main consideration. Even though this is dependent on availability and safety of each single vessel, it is also a function of fleet composition and operations planning. Composition relates to how well vessels fill roles that are complementary to each other, and how total capacities and availabilities match needs and metocean conditions at fish farms. Planning determines if the potential of the composition is exploited. Having a good fleet composition only means having the tools, performance still depends on how the tools are used. This also means that composition and planning are related – what is the best composition depends on how planning is done. With a fleet serving a set of fish farms, not only the exposure of the fish farms, but also when they experience various metocean conditions relative to each other can affect availability and the appropriate composition and operations planning for the fleet. If all fish farms experience the same metocean conditions, unavailability will affect all at the same time, while if they experienced opposite weather there would always be available fish farms. In theory, less correlation can be an advantage, however it all depends on the metocean conditions fish farms experience in relation to service demands they have. Therefore, it is important to understand how well-suited vessels in a fleet are to serve a set of fish farms, in terms of likelihood of weather induced delays, match of functionality and capacities to demands, and ability to respond to urgent needs.

Short-term uncertainty related to sudden service requests and what the exact weather will be at a planned operation is handled by re-planning, chartering vessels for short periods, or simply accepting delays. In a longer perspective focus is more on characteristics of uncertainty and how it can change over time, for example, if there is a shift in types of operations that are requested, or new fish farms are established at more exposed locations. Correspondingly changes in the fleet composition might be beneficial. Comparing fish farms at sheltered locations to more exposed locations, the latter can entail heightened importance of considering effects of weather in matching of vessel designs and fleet composition to serve demands from fish farms while maintaining safety and fish welfare, see Figure 5.

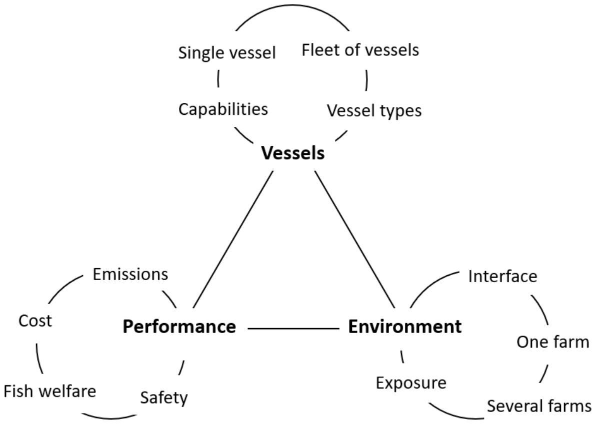

Figure 5. Understanding the relation between vessels and environment is necessary to achieve high performance. Metocean conditions affect vessels during operation, and the effect must be understood at the level of a fleet of vessels serving a number of fish farms.

Design and operations planning is based on an understanding of how vessels respond to environmental conditions, demand for operations, and operational limits. Safety relates both to personnel onboard vessels performing operations in everyday situations, how they approach rare metocean conditions and situations, and their ability to provide response and support in emergency situations.

A network of fish farms is defined based on ownership and organizational structures. If a set of fish farms has the same operational management there usually is a service vessel fleet that operates between these fish farms, and that is reserved for those fish farms. It is common practice that vessel schedules are made independently for single vessels. That is, request being sent directly to a vessel, and changes in plans being met by only making internal adjustments to the schedule of the vessel. One result of this is that two vessels controlled by the same fish farmer can sail long distances to perform one operation each at a two adjacent fish farms, even if one vessel could have done both tasks. Making joint plans for all vessels a fish farmer controls can give large benefits both in initial planning and in re-planning. However, considering larger systems entails more complexity in planning and it is harder to find good solutions that exploit the extra potential. Further, to get the most efficient fleet utilization, the fleet must consist of the most suited vessels, and they must be operated in the most efficient manner. This means that vessels must be suited to the metocean conditions at the fish farms and complement each other with respect to capabilities and capacities. Well suited vessels is synonymous with good vessel design and requires both knowledge of what is needed from each vessel and how to meet those needs through establishing proper functional requirements and design parameters for such vessels (Choi et al., 2015; Gaspar et al., 2016; Gutsch et al., 2016).

A fleet's ability to respond to needs of a network covers both planned and unplanned needs and is concerned with the degree to which operations cannot be performed in time. This is a result of the availability of vessels with appropriate capabilities, which in turn primarily is dependent on capacity of the fleet, applicable weather restrictions, and operations planning. Match between supply of vessel operation capacities and demand for operations at the fish farms is disturbed by weather conditions and operational limits that prohibit operations at certain times and extends the duration of operations at other times. When emergencies occur and emergency response is requested, the support vessel fleet may constitute the primary emergency response resources. Larger fish farms, placed in more exposed and remote areas are likely to lead to a new approach on emergency preparedness in fish farming. It is expected that fish farms will not be allowed to rely on external or public emergency response, and need to provide their own emergency response resources, possibly following the model of offshore oil and gas (O&G) (Forskrift om beredskapsfartøy, 1991; Hoell et al., 2012).

Expansion of a network of fish farms into more exposed areas leads to increased weather exposure in the network which in turn brings three main challenges related to the operations of the fleet of service vessels, see Figure 6.

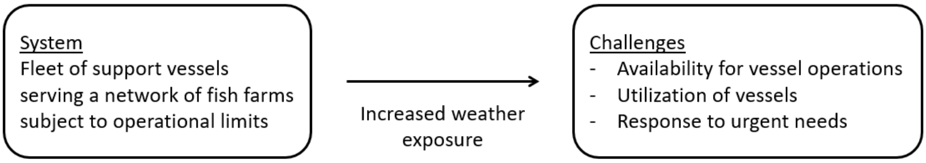

Figure 6. Challenges of increased metocean exposure for vessels operations in aquaculture, with overarching performance metrics.

Availability for vessel operations covers to what degree the different fish farms experience weather conditions that are acceptable for service vessel operations. There is zero availability for vessel operations if all fish farms always experience weather conditions that are too harsh for any vessel operations to be performed. Availability is a result of the operability of individual vessels, which describes how often a vessel can perform operations at a fish farm. How vessels are used and routed determines the resulting utilization of vessels that is achieved, with availability and operability representing upper boundaries for possible utilization. Utilization of vessels strongly affects the economics of vessel operations and can be defined as the portion of time vessels spend on useful actions. Achieving optimal utilization of a vessel fleet serving several fish farms can be a difficult combinatorial problem even without consideration of weather. Introducing weather conditions that lead to reduced operability for vessels, and potentially time-dependent sailing and operation durations with varying weather, significantly increases the difficulty of the problem. An important aspect is the uncertainty of weather forecasts, and how it increases into the future.

The final challenge of Figure 6, response to urgent needs, is motivated by the belief that opening for offshore fish farming will entail new regulations on emergency preparedness, similar to those found in offshore oil and gas. An example is area preparedness where authorities can require stationing of dedicated emergency response vessels close to offshore installations (Rammeforskriften, 2017). Exact details on future regulations are unknown, however it is important to establish insight on the topic. Remoteness to other infrastructure and isolation of fish farms due to rough weather conditions necessitates other approaches such as self-sufficiency for the fish farms in emergency response. In which case the emergency response resources are likely to mostly consist of the service vessel fleet that is fully occupied with performing the planned operations.

Based on the discussion of the research question, three research objectives can be formulated as a summary of what knowledge that must be established. Each objective describes a general direction in which focus of the research project is directed. Each RO is addressed in one or more main article, and thorough presentations are given in Chapter 4. The three research objectives are:

RO 1 Understand vessel suitability in relation to operating environments at fish farms

RO 2 Explore and develop methods for efficient utilization of service vessel fleets in mixed-conditions fish farm networks

RO 3 Investigate the ability of service vessels to respond to urgent needs

1.4 Contributions

The outcome of this PhD thesis is summarized in the following contributions. They meet the research objectives of Section 1.1 and are described in further detail in Chapter 4.

C 1	Framework for assessing the suitability of service vessels in a network of fish farms
Elaboration	Helps understand what vessels are the best to serve a set of fish farms considering metocean conditions, operation demands, interface between vessel and structures, and stakeholder interests.
C 2	Insight on effects of weather in a network of fish farms on service vessel fleet efficiency
Elaboration	Enables well-informed planning of placement of fish farms with respect to effects on operation of the fish farms. Useful when fish farmers expand their operations to include more exposed fish farms.
C 3	Solution methods for routing and scheduling of service vessels
Elaboration	Opening for optimal utilization of vessels, improving mission capacity, cost, emissions, and safety compared to routing strategies used in the industry today.
C 4	Methods for evaluating the performance of a fleet in a scenario
Elaboration	Analyzing vessel operations at fish farms over periods in the order of 100 days for scenarios describing weather and market conditions and demands for operations. For instance a warm summer with high lice pressure requiring more delousing operations.
C 5	Method for assessing fish welfare emergency response capabilities and capacities

Elaboration	Allows for considering outcomes of emergencies when determining preparedness. In addition, bottlenecks and shortcomings of response strategies and resources can be identified and acted on.

1.5 Overview of research papers

The articles of this PhD project are presented in Table 1. Research objectives and contributions covered by the different main articles are briefly accounted for in this section, while more detail is given in Chapter 4.

Table 1. Overview of the research papers.

Research papers	Title	Publication
1	Cost-emission relations for maritime logistics support in aquaculture	Journal of Physics: Conference Series
2	The aquaculture service vessel routing problem with time dependent travel times and synchronization constraints	Computers & Operations Research
3	Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming	Aquacultural Engineering
4	Effective utilization of service vessels in fish farming: Fleet design considering the characteristics of the locations	Aquaculture International
5	Susceptibility to weather induced delays in vessel operations at marine fish farms	Has been submitted to scientific journal

Research paper 1 explores the relations between greenhouse gas emissions, costs, and effectiveness for different fuel alternatives for vessels in fish farming. The effectiveness and emissions of the vessels are considered on a fleet basis, using Discrete event simulation (DES) (Gray, 2007; Kemp, 2003). Reductions in fleet effectiveness due to the fuel types is converted to a cost, related to the inconvenience, and needs for extra resources compared to the most effective fuel alternatives. A pareto front is established for a case study showing the cost of relative reductions in greenhouse gas emissions. Research paper 1 contributes to RO1 and C4.

Research paper 2 presents two solution methods for the aquaculture service vessel routing problem – a version of the vehicle routing problem adapted to the context of aquaculture service vessels. The proposed mathematical model was found to solve small problems to optimality, while the Adaptive Large Neighborhood Search heuristic was found to provide good solutions even for large problems. The contribution of the author to the article was mainly the adaptation of the method to the aquaculture context, translating the practical system understanding to solution method requirements. Research paper 2 contributes to RO2, RO3, C1, C2, C3, and C4.

Research paper 3 investigates the emergency response capacities of well boats in fish farming in the cases of large fish welfare emergencies. Well boats and other aquaculture service vessels that operate according to planned schedules are important resources in emergency response in fish farming. Discrete event simulation is employed to analyze the details of the responses from terminating current operations, to sailing and response actions on site. Research paper 3 contributes to RO3, C1, C2, and C5.

Research paper 4 explores the effect of weather conditions in a network on fish farms on the effectiveness of the related fleet of service vessels. A method was developed for evaluating the effectiveness of a fleet in a scenario. Three parameters describing the weather in the network of fish farms were changed between the scenarios. The similarity in weather between the fish farms, the exposure level at the fish farms, and the duration of the periods of rough weather. Research paper 4 contributes to RO1, RO2, C1, C2, C3, and C4.

Research paper 5 proposes a method for assessing how well a vessel is suited to operate at a set of fish farms, and in cooperation with the other vessels that serve the fish farms. The method considers the historical weather at the location, the operational limits of the vessels, and the distribution of the workload between the vessels. A case study presents the implementation of the method to compare the suitability of two vessels with respect servicing a fish farm. Research paper 5 contributes to RO1, RO3, and C1.

1.6 Delimitations and limitations

The research project is mostly based on the Norwegian aquaculture industry. Possible significant deviations from practices in other countries can therefore be discovered in the project work. Delimitations in terms of applied research approach is discussed in chapter 3 – Research Approach.

Limitations for the research project are mainly related to access to data – both considering the existence of data and if it is available for application in this project. Large amounts of data are collected by the companies and there are initiatives for collection and distribution of data, such as BarentsWatch (BarentsWatch, 2022) and AquaCloud (NCE Seafood Innovation, 2022). However, type and quality of data, and increased willingness to share would be beneficial for research. Quality includes standardization of formats enabling comparisons, collection of metadata, resolution, accuracy, and continuity of time series. Relevant data types for this project cover records of weather, vessel movement and operations, accidents and unwanted events, and performance indicators such as costs, profits, and fish welfare. A result of this limitation is that it is difficult to validate scenarios for models representing fish farming practices, because no reference scenarios with enough information exists. This also means that the understanding of the system behavior is hard to validate.

Dependence on experience in decision-making makes it challenging, in some cases, to get a cohesive understanding of why decisions are made. It can be hard to identify all relevant factors and characterize their effect on decisions. Hence, the behavior of the system as a whole can be perceived as less consistent, that is, similar situations can give different outcomes.

1.7 Structure

The remainder of the thesis is structured as follows. **Chapter 2** reviews state of the art on relevant literature covering the main topics; exposure and exposed aquaculture, vessel design and utilization for normal operation, and preparedness and response to urgent needs. **Chapter 3** presents the research approach, including a classification of the applied methodology and arguments as to why approaches and methods were chosen. **Chapter 4** covers the main results starting with presentations of research papers, before describing their relevance for the research objectives, and finally, contributions of the research project to the literature. **Chapter 5** gives a discussion on validity of the results, and their implications for different stakeholders, in addition to a reflection on how the covid-19 pandemic affected the research project. Finally, **Chapter 6** presents a conclusion and recommendations for further work.

2 State of the art

This chapter covers literature relevant to the research question presented in Chapter 1. The purpose is to establish current state of the art and related research gaps describing the background for the research question and research objectives. Thus, also providing a context for the research contributions of this thesis.

Section 2.1 establishes what exposed aquaculture and exposed operations are, with an emphasis on the term exposure. That is, how the term is understood and what it means in practice, providing an understanding of the environment aquaculture support vessels operate in. Furthermore, common considerations in decision making for site selection are presented. Section 2.2 covers vessel design, vessel fleet composition, and operations planning. Focus is on methods for achieving high mission reliability subject to uncertainty in metocean conditions. However, matching of vessel fleet functions and capacities to service demands is also covered as this is the primary concern with respect to fleet composition and planning. Section 2.3 explores unwanted events that can arise in fish farming, preparedness, and response. Key topics include methods for preparedness assessment and response planning, with focus on logistics and the role support vessels can have as emergency response resources. Finally, Section 2.4 characterizes the scope of the literature study and highlights the relevant research gaps for this thesis.

Topics covered in Section 2.2 are the most central with respect to the research question. Therefore, Section 2.2 is more comprehensive than other sections of this chapter.

Industry specific literature in fish farming mostly covers fish biology, structures, risk and safety, effects of fish farming on the environment, and economics. Little research is published on vessel design and vessel operation specific to fish farming, outside of risk and safety. Literature on these topics is therefore mostly supplied from other relevant industries such as offshore O&G, offshore wind, and shipping.

2.1 Exposure and exposed aquaculture

This section discusses the term exposure and how it relates to exposed aquaculture and exposed aquaculture operations. Main topics are methods for describing and forecasting metocean conditions, knowledge about effects from weather conditions on fish, vessels, and structures, and assessments for site selection for fish farms. The intention is to provide an understanding of the environment vessels operate in, how it affects operations, and what considerations that are made in this regard for site selection.

Fin fish aquaculture started in closed in-land waters and found its way to sheltered areas in the Norwegian archipelago in the 1960’s and 1970’s (Sætre & Østli, 2021). Fish farmers sought areas where there never were large waves, strong currents, strong winds, or other environmental conditions that could harm the fish or fish farm structures. Fish farm structures were not robust, often made from wooden planks, and operations were performed from small, open boats, see Figure 7. As the industry expanded, fish farms were established in areas with harsher weather conditions and, in parallel, fish farm structures and support vessels advanced technologically, see Figure 8. The result is that modern fish farms can be operated in areas that were considered too weather harsh in the 1960’s or 1970’s. As an example, modern flexible pens, as shown in Figure 8, can be built to withstand significant wave heights of 6 meters and current speeds of 1.2 m/s (ScaleAQ, 2022).

Figure 7. Fish farming in Norway in 1974 (NRK, 1974).

Figure 8. Fish farming in Norway in 2019.

New fish farm concepts for exposed locations can indicate significant changes to current practices for operating fish farms, including increased integrated functionality at the fish farm structures. For instance, crowding of fish for delivery at Ocean Farm 1 employs moving bulkheads that are part of the structure (Ocean Farming et al., 2019). However, they still require vessels to perform operations and the scope of adoption of these concepts in the industry is still an open question. The concern regarding vessel operations at exposed fish farms, and thus the motivation behind integrated functionality, is not as much the technical feasibility of operations being performed when needed, as it is the cost level. The challenge is to achieve safe and reliable operations with good fish welfare at exposed locations that can compete on cost with sheltered fish farming. Accomplishing this necessitates a thorough understanding of the differences in operating environment and thus understanding exposure.

2.1.1 Exposure

Cambridge Dictionary defines exposure as "the fact of experiencing something or being affected by it because of being in a particular situation or place" (Cambridge Dictionary, 2022). The usefulness in characterizing exposure is related to the effects that entail from exposure. Combining a subject and a particular exposure gives an effect according to a relation, which might or might not be known, see Figure 9. Useful measures for exposure can aid decision makers considering the resulting effects, for instance, enabling them to determine and adhere to limits for exposure to avoid unwanted consequences.

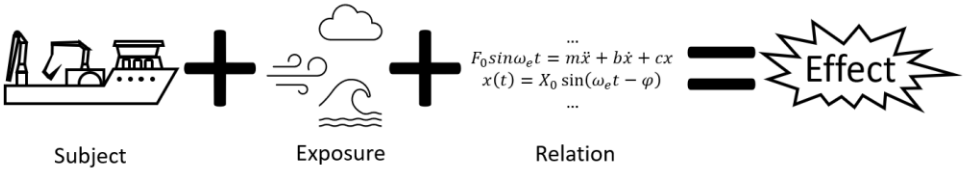

Figure 9. Interest in characterizing exposure is based on interest in effects from exposure.

Exposure is a widely used term in epidemiology and ergonomics, and the use corresponds well with the dictionary definition. In epidemiology it describes the interface between an organism and the environment, for example, the amount of CO people experience (W. Li et al., 2018). While in ergonomics it is related to exposure to risk-factors (David, 2005), such as human exposure to vessel motions in offshore O&G (Haward et al., 2009), and other "unfavorable health exposures" related to work conditions (Thorvaldsen et al., 2020). For Atlantic salmon environmental exposure describes metocean conditions fish experience, such as water temperature, current speed or even exposure to harmful jellyfish (Hvas, Folkedal, Imsland, et al., 2017; Hvas, Folkedal, Solstorm, et al., 2017; Powell et al., 2018). While it is common to refer to exposure as binary, that is either something experiences exposure or not, in the literature exposure is often characterized in three dimensions: Intensity, duration and frequency (Vallero, 2014). A quantitative expression for exposure in epidemiology is as the time integral of a time dependent intensity, which means that exposure is understood as accumulative, Figure 10. That is, for instance, exposure of constant intensity gives larger effects as time passes. This is also well known from ergonomics, for example, in relation to occupational injuries. In other cases it is of more interest to consider exceedance of threshold values, or some statistical property describing the intensity in time, for example, mean time between waves more than 2m high, or the highest expected wave in a year, see Figure 11.

Exposure assessments, characterizing exposure, are often performed either to characterize the input to a known output so that a relation can be established, or to determine the acceptability of a situation based on a known relation to effects (Vallero, 2014). Dietary guidelines is an illustrative example of the latter, where the exposure to food, that is, food intake, is characterized in terms of daily intake of different foods, and there are known relations between exposure and effects (U.S. Department of Agriculture & U.S. Department of Health and Human Services, 2020).

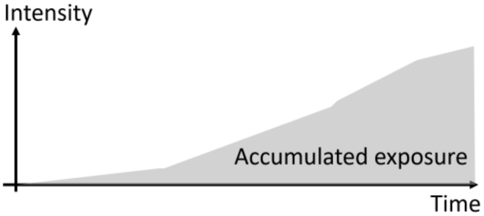

Figure 10. In some cases it is useful to characterize exposure as accumulating over time.

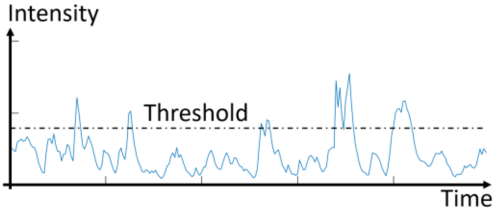

Figure 11. Number of times a threshold intensity is exceeded can be an expression for exposure.

In fish farming, exposure is usually related to metocean conditions at fish farms such as wave, wind, and current conditions, or more specifically to what degree fish farms experience rough metocean conditions such as large waves, strong winds or strong currents (H. V. Bjelland et al., 2016). Fish, structures, vessels, and personnel are all affected by the weather conditions in different ways, which means that an expression for exposure to cover all aspects must have multiple parameters. In addition, it must consider on what form exposure should be represented, for instance, as integral of intensity over time or by peak intensity for a given period. A fish farm or vessel has very little memory of earlier weather conditions like experienced waves, unless the exposure intensity for a period was high enough to give some sort of lasting damage or deformation. On the other hand it does make sense to talk about exposure to current as accumulating with respect to the swimming capacities of fish because the fish can endure stronger currents for shorter periods (Hvas & Oppedal, 2017). Also, with respect to operation of fish farms, both frequency and duration of periods with challenging weather conditions do affect the severity of the effects. If a fish farm is unavailable for vessel operations for short periods it may not necessarily affect operation of the farm, however unavailability for long periods can have severe consequences. One example is high mortality or loss of growth if feed deliveries at the fish farm are absent for long. Severity of effects resulting from metocean conditions can also be dependent on the direction of the weather variable due to local geography, topography and how the fish farm is oriented, among other aspects. In addition, the geographical extent of fish farms, as illustrated in Figure 2, entails that exposure can vary between pens within a fish farm.

It seems difficult to establish a general aggregate term for exposure that would be useful in decision support for all applications, for instance site selection, fish welfare and vessel design, due to the variation in considerations. However, it could be useful with a standardized description of what is covered by exposure and how it is measured for characterizing a location, so that experience is applicable between different fish farms. As stated in Froehlich et al. (2017) "consistent metrics are needed for a comparable framework to guide sustainable offshore aquaculture research and development globally". In NS9415 – Norwegian standard for floating aquaculture farms - wave height, wind speed, and current speed for certain return periods are used to specify load conditions for dimensioning of structures for a location (Standards Norway, 2021). However, it and other regulations and standards concerned with the metocean conditions at locations make no attempt to draw the line between what is and is not exposed. As discussed initially in Section 2.1, the bar for what is considered rough metocean conditions, and thus what is considered exposed, is not fixed. Despite the lack of a general definition for whether a fish farm is exposed, there seems to be a general understanding that the term is appropriate if metocean conditions regularly intervenes with plans for vessel operations.

Lader et al. (2017) performed a classification of all fish farms in Norway based on exposure to wind waves by performing fetch analysis for the locations. Fetch analysis maps distance from a fish farm to nearest land in all directions and can in combination with wind data be used to estimate wind waves at a position. The method gives a clear visual impression of exposure, as shown in Figure 12. Classifications, A through E, with E being the most exposed, are based on significant wave height of 1-year return period according to an attachment to Standards Norway (2009).

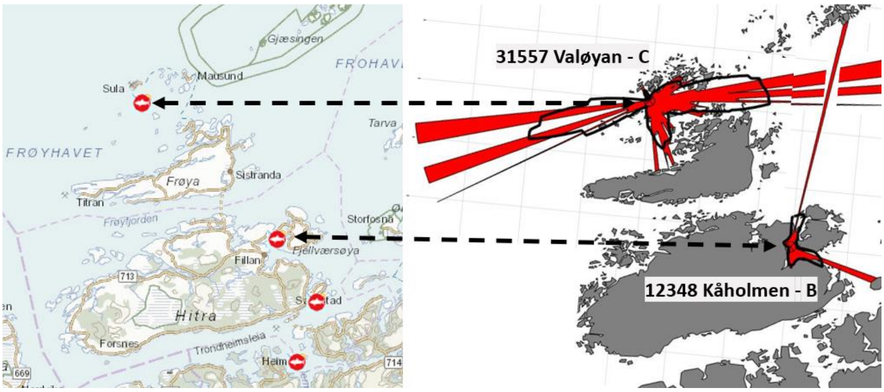

Figure 12. Differences in exposure can be the result of different fetch lengths from different directions. Here the Valøyan location is compared to Kåholmen.

Exposed aquaculture is used as a collective term for fish farming at exposed fish farms. Use of the term exposed aquaculture is motivated by large differences in weather conditions between fish farms and observed needs for new approaches and solutions as the industry expands into ever rougher metocean conditions. The term is useful to describe a shift in the approach to designing and operating fish farms in rough metocean conditions. A complete rethinking of how fish farming is done is required to be able to transition offshore, covering new technology, logistical solutions and new methods enabling safe and efficient operations (H. V. Bjelland et al., 2016). An example of this shift is seen among the new fish farming concepts presented by several companies, including Ocean Farm 1 from Salmar, and Havfarmen from Nordlaks (Ocean Farming et al., 2019; Robertsen et al., 2021). Exposed aquaculture also entails regulatory changes, as noted by Davies et al. (2019) when they consider what they refer to as offshore aquaculture. Offshore aquaculture is another term that is not well defined and is largely used interchangeably with exposed aquaculture, however, the term can be understood to be closer to open-ocean aquaculture. Langan (2012) states that open ocean aquaculture is "generally accepted to mean fish farming in locations that are subjected to ocean waves and currents and are removed from any significant influence of land masses". The lack of useful definitions for describing offshore aquaculture is problematized in Froehlich et al. (2017), where they find that there is large variation in how the term is used.

Characterization of exposure should describe metocean conditions in a way that is relevant for decision-making. Rougher weather affects fish welfare, safety, and quality of operations, and it is important to understand how. Developing and employing new methods depends on an understanding of correlations between metocean conditions and effects. This ability to define exposure in a useful way is determined by the ability to describe metocean conditions, which is the topic of the next section.

2.1.2 Describing metocean conditions

Talking about weather exposure necessitates an understanding of marine weather, including how weather is described, how the dynamics are understood, and how marine weather can be used in analysis and design of marine structures and vessels. Design and planning must consider probable weather scenarios, but the stochastic property of weather makes it impossible to predict future weather with 100% certainty. Therefore, good decision making with respect to weather relies on the quality of prediction methods. That is, how to best prepare for the weather the fish farm and vessels will experience in operation.

Waves are often considered the most important environmental variable in marine weather due to the large effect on responses in structures and vessels. The most basic description of a wave is a long-crested, regular wave with a fixed amplitude and period. Realistic sea is short-crested, irregular, and changing, which means that it is composed of a set of long-crested waves propagated from different directions that have different and changing periods and amplitudes (Myrhaug, 2005). Distribution of amplitudes for waves of different periods are described in terms of wave spectrums that "represent the distribution of wave energy among different frequencies of wavelengths for a sea state" (Orimolade & Gudmestad, 2016). Wave spectra are geographically dependent and are found from analysis of large historical data series. Therefore, wave spectra are usually not available for the considered location. A few well-known spectra are widely used as an approximation, including JONSWAP, Pierson-Moskowitz, and Torsethaugen (Torsethaugen & Haver, 2004). Some spectra are double peaked, which means that they consider sea states with two wave systems; swell and wind sea. It should also be mentioned that spectra are established for fully developed sea, based on the assumption that "if the wind blew steadily for a long time over a large area, the waves would come into equilibrium with the wind" (Pierson & Moskowitz, 1964). This is a simplification which is never true, especially for fish farms which usually have limited fetch lengths. Wave steepness - the ratio of wave height over wave length – is closely related, and is an important characteristic in the consideration of wave loads (Bitner-Gregersen & Soares, 2007). In addition to the spectrum for the energy distribution between the frequencies, there is also a distribution in the directionality of the waves (Portilla-Yandún et al., 2019). Wave conditions for a short period – a wave state - can be assumed to be constant and can thus be approximately described by a wave spectrum and a distribution for the directionality. The behavior and propagation of waves in coastal areas are affected by interactions with land and seabed, a complexity that is presented in Holthuijsen (2007), but the topic is not discussed any further in this thesis.

Long-term wave conditions at a location describe distribution of different wave states over time. An example is the Hs-Tp scatter diagram which is a tabular representation of correlation between significant wave height (Hs) and the peak spectral period (Tp) (Lucas & Soares, 2015), and the portion of time different wave states occur in an area. Probability distribution is another way of describing stochastic properties of physical variables like wave height. Basic theory on uncertainty and probability, and common distributions for physical variables, such as gauss, lognormal and Poisson, are covered in Leira (2005). Central points are parameter estimation and validation of distribution selection. Further characteristics of stochastic processes, for instance, autocorrelation, cross-correlation, and narrow and broad band processes, are covered in (Newland, 1993). Katalinić & Parunov (2018) derive a joint distribution for Hs-Tp based on 24 years of hindcast data, and a proposal for a joint model of wave height and wave steepness is presented in Antão & Soares (2014).

Often it is useful to describe the weather conditions in terms of several weather parameters, for example including wind and current. This is relevant in fish farming vessel operations because operations can be sensitive to both waves, wind and current conditions. Joint probability models (JPM) describe probabilities of weather states constituting more than one parameter, for instance, how wave height is correlated with wave direction or wind speed. Sagrilo et al. (2011) presents a method based on the Nataf-transformation to make joint distributions for waves, wind and current, including correlation between direction and intensity for all variables. Detailed descriptions of sea states including intensity, directionality, and expressions for spreads requires large amounts of joint data, and it is a challenge to find good models (Bitner-Gregersen, 2015; Bruserud et al., 2018). Bitner-Gregersen (2015) uses the Conditional Modelling Approach (CMA) to model data from four locations considering twelve variables. A key problem is related to the combination of circular and linear characteristics, for which Haghayeghi & Ketabdari (2018) has proposed a solution for three variables, wave direction, wave height, and wave period, using CMA. Another problem is related to establishing representations of the dependencies between several variables, for which bivariate copulas have been proposed as building blocks (Montes-Iturrizaga & Heredia-Zavoni, 2016). Further, the dependencies can be significantly asymmetric, as discussed in Y. Zhang et al. (2018). An example of a bivariate relation shown as a dot chart, and some symmetrical copulas are shown in Figure 13 and Figure 14, respectively.

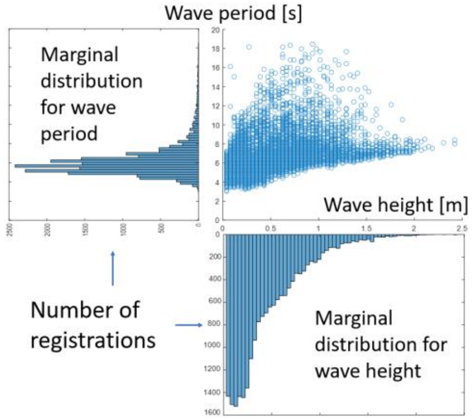

Figure 13. Marginal distributions for wave period and wave height, and dot chart for correlation between the variables. Correlation is clearly not linear or symmetrical. Registrations from SFI EXPOSED.

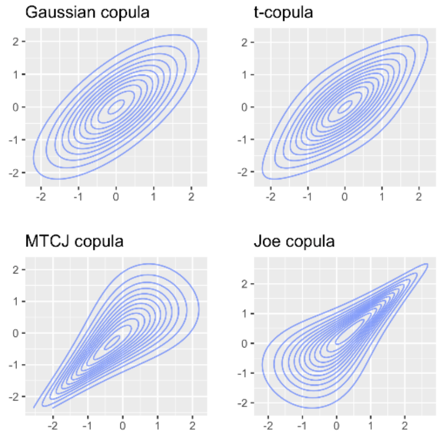

Figure 14. Examples of symmetrical copulas. From Chang (2019).

The basis for all models and representations of marine weather is registered data, mostly based on point observations, such as buoys anchored at fixed positions, see Figure 15. Advanced weather buoys can register many variables, including wind speed and direction, current speeds and directions at several depths, temperature, salinity, and wave characteristics derived from registered surface accelerations. SFI EXPOSED, projects P8 and P18, has deployed three buoys at fish farms in mid-Norway registering all these parameters, covering approximately two years on average. This is data that has been available for this thesis work. Sea states are often established for one-hour or three-hour periods, with buoys returning only an aggregate statistic from the period for each parameter, for example, the average current velocity and average direction. Therefore, it can be important to know how the aggregation is calculated, depending on how data is to be used.

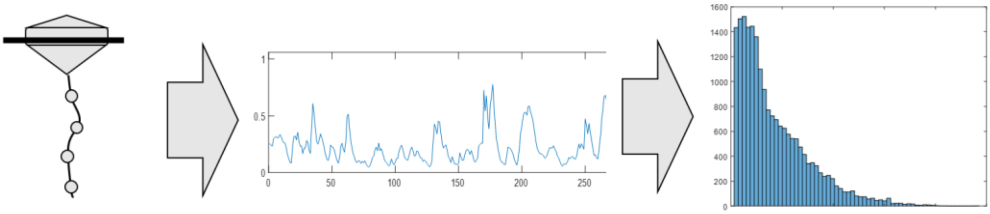

Figure 15. Weather buoys make registrations in the time domain which are used to characterize metocean conditions through statistical analysis.

Combining registrations with mathematical models enables the generation of hindcast data, in a process referred to as reanalysis which calculates how the weather conditions were at points between the observations (ECMWF, 2022), see Figure 16. ERA5 is an example of a reanalysis of the global climate made by the European Centre for Medium Range Weather Forecasts (ECMWF) (ECMWF, 2018). Hindcast data is a result of the available data and applied model. Campos & Soares (2016) performs an assessment of three different hindcasts in the North Atlantic Ocean. Further, the resolution from hindcast data such as ERA5 is often relatively coarse, for example with a resolution of 0.25 degrees, which can necessitate downscaling for certain applications. Reistad et al. (2011) presents a dynamical downscaling, making a high-resolution hindcast.

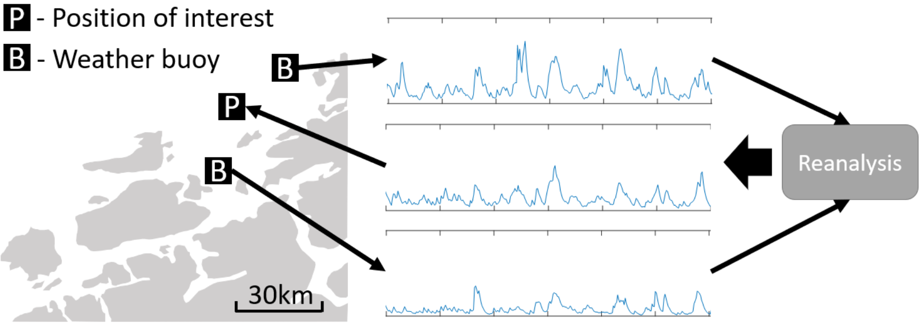

Figure 16. Registrations from weather buoys can be combined with reanalysis to establish estimates on time series for variables at positions without weather buoys.

One important application of marine weather analysis is design of offshore structures and vessels where dimensioning load conditions must be established (Bore & Amdahl, 2017). This requires estimation of extreme values from statistical models for variables such as currents (Bore et al., 2019) and waves (Laface & Arena, 2016). Standards

Norway (2021) defines environmental loads for dimensioning based on current, wind and wave conditions according to return periods. The Hs of a given return period is the Hs that is expected to be exceeded with an interval equal to the return period. Accuracy in estimation of extreme values is affected by both the applied model and the sample size. Soukissian & Tsalis (2018) evaluates the fit of different estimators for the General Extreme Value (GEV) distribution.

Another important application of marine weather analysis is in generation of synthetic time series, which enables analysis of behavior in the time domain (De Masi et al., 2015). A synthetic time series is a series of sea states that is generated based on statistical characteristics of weather in an area. This requires a description of how sea states develop, that is, for instance, probability distributions for next sea state given current sea state. Sandvik et al. (2019) evaluate three different models: Markov chain, Vector Autoregression (VAR), and Vector Autoregressive Moving Average (VARMA). Time series are necessary to evaluate availability for weather restricted operations that last longer than one sea state. Synthetic time series are useful because they provide realistic realizations based on statistical characteristics of a given geography. Potentially an infinite number of realizations can be generated enabling large-scale testing and statistical analysis in time series characteristics. Markov models are common in synthetic time series, and enable multi-variate series (De Masi et al., 2015).

Finally, operational weather forecasting is used in operations planning of weather restricted operations, to give short-term predictions with high fidelity. Forecasts are based on observations and mathematical models. There is significant uncertainty related to accuracy, and it increases further into the future (Natskår et al., 2015; Zyczkowski et al., 2020). However, certainty of forecasts is improving (Janssen & Bidlot, 2018), and many fish farmers consider 2-3-day forecasts to be reliable.

2.1.3 Metocean effects on fish, structures, and vessels

Section 2.1.2 covered how weather is described and what type of information is available about weather at fish farms. Usefulness of this knowledge is related to how it is applied to study effects on fish, structures, and vessels to gain knowledge in decision making related to planning and operation of fish farms. Most operations in fish farming have interactions with fish either directly or indirectly, and therefore it is important to consider the health and stress level of the fish before initiating an operation, see Figure 17. Like all living animals, there is a limit to the total stress fish can handle, and the effect of environmental conditions thus determines what stress it can take from operations (Press, 2022). Likewise, most operations involve some level of interaction between vessel and structures, see Figure 18. Thus, understanding behavior and design of structures is a necessity to get the full picture on limitations and responses for vessel operations. This section covers effects of weather and environment on fish, structures, and vessels.

For fish, weather exposure is mostly related to wave height, wave steepness, and current speed (Hvas et al., 2021; Johannesen et al., 2020). Johannesen et al. (2020) study how Atlantic salmon are affected by "wavy" conditions. The study indicates that fish behavior and vertical distribution of fish in the pen depends on a combination of factors including wave parameters, current, and time of day. According to Vikebø (2020) farmed salmon can become sea sick when transported in well-boats, however it is not studied how this transfers to fish in pens. Critical swimming speed is the upper limit for the swimming speed fish can maintain over long periods without serious negative effects to fish welfare. If fish are put in an environment where current speed inside the cage is above critical swimming speed for long periods, this will harm the fish. Critical swimming speed depends on size, temperature, and has individual variation (Hvas, Folkedal, Imsland, et al., 2017; Remen, Solstorm, et al., 2016). Swimming capacity is also affected by, for example, gill parasites (Hvas et al., 2021; Hvas, Karlsbakk, et al., 2017). In addition to forcing the fish to swim, current is what drives water exchange in open pens and ensures a supply of dissolved oxygen. Shielding skirts used against sea lice and other obstructions that affect the flow of water can lead to reduced oxygen saturation in the pen (Jónsdóttir et al., 2021).

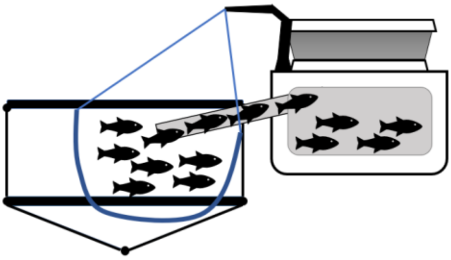

Figure 17. Vessel operations stress the fish, some more than others. This illustrates crowding of fish and pumping onto a well boat. One of the more stressing operations.

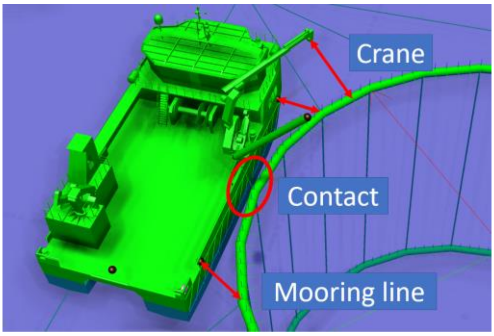

Figure 18. Interactions between vessel and structures during operations can include forces on mooring lines, contact between hull and floating collar, and forces in lines extended from cranes. In addition, thruster jets can cause significant currents giving drag loads.

Temperature is an important weather parameter for growth and welfare of fish. It is well established that water temperature affects the growth rate of Atlantic salmon (Austreng et al., 1987). Growth rate increases with temperature and is in the range of 6-8 times higher at 16°C than at 2°C according to Austreng et al. (1987). However, Kullgren et al. (2013) indicates that long term growth is better for 12°C than 18°C. maximal growth is dependent on the saturation of dissolved oxygen being above a certain limit, which is highly temperature-dependent (Remen, Sievers, et al., 2016) which also finds the highest specific growth rate (SGR) at 15°C, compared to 7, 11, and 19°C. Atlantic salmon needs both the levels of dissolved oxygen and the temperature to be within a given range to thrive. According to Stehfest et al. (2017), fish avoid areas with less than 35% saturation of dissolved oxygen and areas where water temperature is higher than 20.1°C. In a study where Atlantic salmon were exposed to rapid temperature changes in both fresh water and salt water Vargas-Chacoff et al. (2018) found that temperature and salinity have an impact on cellular stress response. Some variables such as nutrients, oxygen, and temperature affect the welfare of fish independently of the enclosure or environment the fish are in. Other variables such as waves and current have an increased effect when fish is kept in pens, because the fish then do not have the same possibility to move away from weather effects they dislike, and they can get bruises and scratches from coming in contact with the net or other components.

Unlike fish, that are more suited to certain metocean conditions, fish farm structures can be designed and dimensioned to suit any condition. However, this requires a thorough understanding of how weather affects structures, while of course also being a cost consideration. Requirements for dimensioning of fish farms, with objective of preventing escapes, is covered in Standards Norway (2021). It contains the design, construction, and use phases, and goes into detail on materials, interactions, location surveys, loads, and various components. Moe et al. (2010) presents a method for performing structural analysis of nets, finding drag loads and deformations of a net in current. Effect of heaving waves on an elastic net panel, in terms of loads and deformation, is investigated by Ito et al. (2011). The study shows that "added mass, damping coefficients and wave exciting forces decrease (as solidity decreases)", and this feature is the same as for rigid nets that were studied in Ito et al. (2010). Xu et al. (2011) study responses of a cage system with a cage and mooring in irregular waves, covering tensioning in lines and motions of floating collar. A model for hydrodynamic response of a mooring frame with multiple cages is presented in Xu et al. (2012), that allows for analyzing tension forces in lines, while a numerical investigation of a pen system, that is, realistic fish farm structure, in combined waves and current was performed by Shen, Greco, Faltinsen, et al. (2018). Advantages and disadvantages of various net pen designs are considered with respect to operation in a "high energy environment" in Chu et al. (2020). Gansel et al. (2018) perform towing tests on a pen that is 12 m in diameter and 6 m deep, in a fjord environment, measuring drag, net deformation and reduction in cage volume. Net deformation is also studied in Johannesen et al. (2022) where waves and current were found to reduce internal volumes of pens, leading to higher density of fish.

Introducing interaction forces between fish farm and vessel makes it necessary to consider both how weather affects motions of the vessel as well as the coupled vessel-structure-system that occurs during vessel operations at fish farms. Vessels have six main degrees of freedom; heave, sway, surge, yaw, roll, and pitch, see Figure 19. Freely floating vessels have motions induced by wind, waves, and currents in addition to their own machinery. Wind and current forces are determined by cross-sectional area and shape, above and below the water line, respectively. Waves induce motions for the various degrees of freedom according to transfer functions based on vessel characteristics like hull shape, center of gravity, mass distribution and loading condition, see Figure 20, Figure 21, and Figure 22.

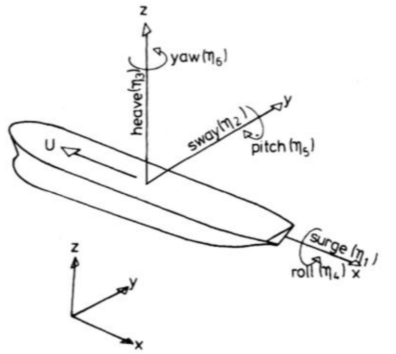

Figure 19. Vessels have six degrees of freedom; surge, sway, heave, roll, pitch, and yaw. Figure from Faltinsen (1993).

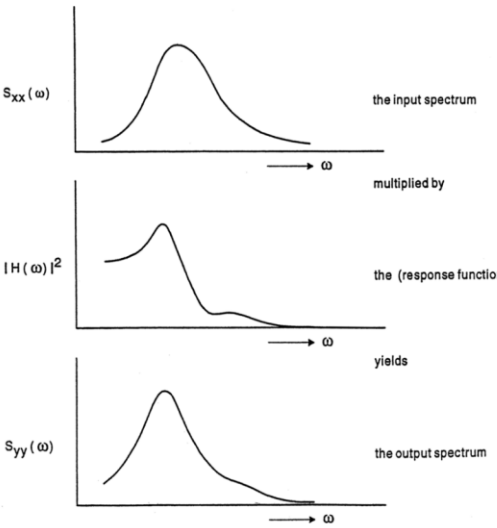

Figure 20. Input spectrum describes waves, response function is a result of vessel design and loading, and output spectrum describes vessel responses. Figure from Steen (2014).

These transfer functions describe the normalized response as a function of wave period and are also referred to as Response Amplitude Operators (RAO). RAOs depend both on heading, see Figure 21, and vessel characteristics such as main dimensions, see Figure 22. Rusu & Soares (2014) combine weather forecasts and “transfer functions for different ship speeds and headings” to anticipate vessel responses in different areas to help fishing vessels plan their operations. Loading conditions can vary significantly for aquaculture support vessels, for example, for well boats before and after unloading, and changes in both cross-sectional areas and center of gravity affect responses. Stabilizers can be used to improve stability and reduce motions, with examples being anti-rolling tanks, gyro stabilizers, active fins, ballast systems, and bilge keels. In rough metocean conditions none of these may be sufficient, so W. Yang et al. (2019) propose heave plates to reducing heave motions for small crew transfer vessels in offshore wind. The problem they solved was related to relative motion between vessel and wind turbine pile. Shen et al. (2019) simulates a well-boat operating at a pen in irregular waves and current, studying the dynamic response of the coupled system and how the well-boat induces loads and stresses on the fish farm. In these situations vessel motions are affected by connections to other structures or equipment, for instance, operation of large cranes or interaction forces to a net (Rokseth et al., 2017), see Figure 18.

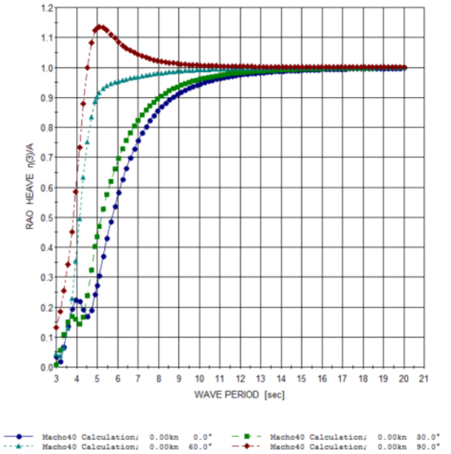

Figure 21. Response Amplitude Operator for heave for an aquaculture service vessel for different headings. Figure from Stemland (2017).

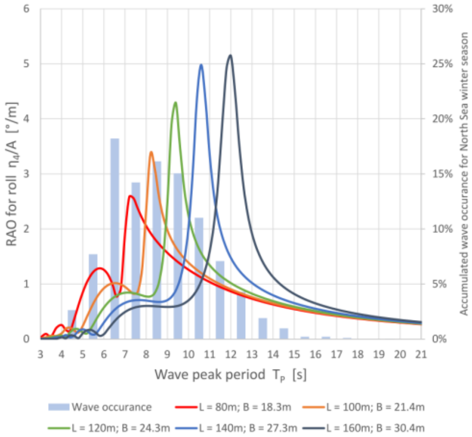

Figure 22. Response Amplitude Operator for roll for offshore construction vessels with different design parameter values. Each graph is a variation of main dimensions of the same base vessel. Figure from Gutsch et al. (2020).

2.1.4 Site selection

Site selection is the process of determining where to place fish farms and can be done either in parallel with or prior to fish farm design, that is, placement and design of a fish farm within the location. Site selection covers a range of considerations such as production environment with respect to fish welfare, and distance to other fish farms and infrastructure such as hatcheries and slaughterhouse.

The primary concern in site selection is suitability for fish, both because it is the main asset, and because it cannot be adapted to metocean conditions to the same extent as structures and vessels, as previously mentioned. Oxygen levels, water quality, and temperature are important factors for fish welfare and growth rate, and acceptable levels is a premise for further consideration of a particular site. Acceptable levels for oxygen saturation depend on temperature, and the minimum level required for maximal feed intake is highly dependent on temperature. According to Remen, Sievers, et al.

(2016) 42% is required at 7°C while 76% is required at 19°C. Current drives exchange of water in the pen and should thus be strong enough for suitable oxygen saturation, but it should also not exceed the swimming capacity of the fish (Hvas, Folkedal, Solstorm, et al., 2017; Jónsdóttir et al., 2019). Albretsen et al. (2019) have made a report on where in the ocean outside Norway metocean conditions are suitable for Atlantic salmon in open cages. Dale et al. (2017) did an assessment including several parameters and found that there are very few areas for offshore fish farming if current speed and significant wave height cannot exceed 0.4m/s and 4.5m, respectively. The limit for current speed is based on requirements from Norwegian Food Authorities for transfer of smolt, and the limit for significant wave height was based on the characteristics of what was the most exposed location in Norway as of 2017 (Dale et al., 2017).

Lice pressure, which largely depends on distance to other sites and current and temperature conditions (Akvabiosikkerhetsforskriften, 2022), is another key factor in site selections (Abolofia et al., 2017). Distance to other fish farms is also considered with respect to spread of infections (Ådlandsvik, 2019). Jónsdóttir et al. (2020) analyze current and oxygen conditions inside pens with lice skirts at two locations, showing that oxygen levels also depend on stratification – that is, mixing of water layers.

Even though structures can be engineered to withstand desired loads, there are considerations that make some metocean conditions preferable compared to others, which in turn determines suitability of a location. Fish farm concept type and dimensioning relates to cost both with respect to complexity in construction and operation, and use of resources. Falconer, Hunter, Scott, et al. (2013) state that “Each cage type has its own engineering tolerance levels and is designed to cope with a certain range of environmental conditions” and they present a model to find where different engineering designs are suited, using Geographical Information System (GIS). Assessing the suitability of a location for a structure requires determining the ultimate limit state at the location (Bore & Amdahl, 2017). Site suitability for structure-weather relation depends on available technology and design methods (Langan, 2010; Shainee et al., 2013). Different concepts and mooring systems for open ocean finfish farming are presented in Langan (2012).

Competing interests, such as alternative uses of areas or opposing public opinion has a big impact on site selection. For offshore fish farming, available areas are likely to be heavily restricted due to allocation of areas to other interests. Norwegian Ministry of Trade Industry and Fisheries (2019) lists fisheries, maritime traffic, travel, military, O&G, renewable energies, pipes and power cables, communication, storage of CO2, and deep-sea mining as possible conflicting interests. However, according to Gentry et al. (2017) even after accounting for existing ocean uses and limitations, most coastal countries have large suitable areas for aquaculture. DNV (2021) forecasts a large increase in both sheltered and offshore finfish aquaculture by 2050. Stelzenmüller et al. (2017) discuss how GIS can be used in marine spatial planning (MSP) and presents a case for co-location of offshore wind energy and aquaculture.

Competing interest, especially related to travel and tourism, is closely related to public opinion which in turn can affect approval of new fish farms from the government. One of these concerns is the visual impact of the fish farms both in the seascape and the on land infrastructure (Falconer, Hunter, Telfer, et al., 2013). How costs and benefits are distributed between local and central governments also affect the willingness to designate areas to fish farming locally (Aanesen & Mikkelsen, 2020). Public opinion is also strongly affected by how fish farming affects the environment, and it may prohibit placement of fish farms even in areas where there are no competing interests as such. Fish farming can affect water quality, predator wildlife, other salmonids, and seabed. Localized effects on water quality are studied by Dunne et al. (2021). A water quality index is developed by Tallar & Suen (2015) to assess pollution from aquacultural activity. How local wildlife can be affected is described both in Dempster et al. (2009) and in Cermaq et al. (2012). Spread of marine parasites affects wild salmon (Lien et al., 2021), and is strongly seasonal (Samsing et al., 2017). Many concerns of environmental effects of salmon farming in Chile are raised by Quiñones et al. (2019), including use of pesticides and antibiotics, fish escapes, and supply of nutrients possibly causing HABs. These concerns are not new, and many of the same issues have previously been observed in Holmer (2010) and Asche et al. (1999). It should also be mentioned that there are significant differences between countries as, for example, there is little use of antibiotics in Norwegian fish farming (Norwegian Seafood Council, 2021). How fish escapes from fish farms affect the environment and wildlife is discussed in Sætre & Østli (2021) and Wennevik et al. (2021). Dispersal of fish farm debris is another concern which is covered by Hartstein et al. (2021).

Complying with rules and regulations directs the whole process of site selection and can affect how various concerns are weighted by the decision maker. It may also be the case that laws and regulations are not “adapted” to the industry, “making offshore aquaculture permitting and leasing a lengthy and expensive procedure that’s rife with uncertainty” (Lester et al., 2018). For example, in Norway a new, separate regulation is being developed to govern offshore fish farming, supplementing the existing production area regulation that governs fish farming closer to shore (Norwegian Directorate of Fisheries, 2022; Produksjonsområdeforskriften, 2017).

Site suitability assessments, and subsequent site selection, should be performed through a holistic analysis of the various available areas. Methods for multi-criteria analyses, proposing how to consider and weigh different interests and concerns, are presented in the literature. Dapueto et al. (2015) present a spatial multi-criteria evaluation (SMCE) that considers multiple stakeholder interests, including environmental, economic, and social aspects. SMCE is also used in a case study for placement of fish farms off the Algerian coast by Chahinez et al. (2020). Papageorgiou et al. (2021) evaluate sustainability of growth in the Mediterranean after integrated management plans were adopted. Pérez et al. (2005) propose a standard methodology for using GIS in site selection considering a large number of factors, and Galparsoro et al. (2020) performed an extensive study on "(…) main obstacles and risks hindering the growth and expansion of marine aquaculture". Jansen et al. (2016) lifts the discussion of also considering potentials for multi-use facilities in these evaluations.

Based on how metocean conditions affect fish, structures, and vessels, and differences in metocean conditions between locations, site selection determines the premises for operation of the fish farm. Effect of weather on operation of fish farms is not extensively considered in site selection, even if the result can be that a fish farm is established but cannot be properly operated and must be closed. Possible reasons include a lack of good methods for assessing effects of weather on vessel operations and prioritizing other concerns.

Section 2.1 has covered the terms exposure and exposed aquaculture, as they are understood in the industry today, where the latter has no standard definition, but a clear purpose of differentiating the operation of fish farms with challenging metocean conditions from that of sheltered fish farms. Marine weather was discussed, in Section 2.1.2, in terms of how it is described and what methods are available for analyzing and predicting metocean conditions at a fish farm to consider in design, dimensioning and operations. Section 2.1.3 presented how weather and environment affect fish, structures, and vessels, giving an understanding of how knowledge of marine weather can be utilized in decision processes. Finally, in Section 2.1.4, considerations in site selection were presented, showing that the decision on where to place fish farms is not free to optimize for availability for vessel operations. In fact, a research gap that is addressed in the contributions of this thesis is the lack of methods for assessing effect of site selection on vessel operations. In total, Section 2.1 provides a foundation for understanding operational environment of aquaculture support vessels, and the "decision environment" of fish farmers, where operation of the vessels is just one out of many concerns to consider in decision processes.

2.2 Design of vessels and operations planning

Vessel fleet composition and utilization determines how well operational demands at fish farms can be met. Capacity matching between supply and demand, costs, variations in functional requirements for different operations, and weather restrictions are among the factors that makes optimal fleet composition and utilization both beneficial and difficult to achieve. Based on an understanding of need for operations and marine weather environment at fish farms, decisions can be made on vessel design, fleet composition, and fleet utilization to achieve the desired service level.

This section elaborates on methods and tools in the literature that cover the general maritime versions of fleet composition, routing, and scheduling problems. In addition to the basic problems, extensions are considered, with emphasis on effects from weather on operations. First, in Section 2.2.1, literature is presented on designing a vessel according to a purpose and an operating environment, including methods for determining operability. Then, in Section 2.2.2, focus is shifted to the fleet level, where the goal is to compose a fleet able to provide the requested support services to one or more fish farms. Finally, in Section 2.2.3, operation of the vessel fleet is discussed, with the objective of achieving high utilization subject to the operability of individual vessels.

2.2.1 Vessel design

Vessel design is the process of arriving at a detailed description of a form and layout for a vessel. Main dimensions, hull shape, capacities, propulsion, and general arrangement (GA) are among what must be specified. The core design task is a tradeoff between technical and economic objectives, complying with constraints and achieving the best balance between all considerations (Parsons, 2004). The process is inherently challenging because of the nature of abduction and high-quality requirements for solutions to be competitive. Abduction is the process of combining a rule and result to arrive at a case, one of three types of reasoning with the two others being deduction and induction (Coyne et al., 1990). Abduction is the essence of design in the sense that rules are known, for instance, laws of physics, and the result is described, for example in terms of a functional description, and from there a design is to be found. The challenge is that while deduction gives one, clear answer, abduction does not. In plain text, assessing if a vessel design will float yields a yes or no answer, while there is an infinite amount vessel designs that will float.

Design + physics = will float (performance)

Will float (performance) + physics = number of possible designs → ∞

The design process is therefore usually based on proposing solutions and then evaluating their performance with respect to functional requirements – narrowing the solution space until a single design is reached. Point-based design seeks to quickly determine a feasible solution which is then optimized, a process that can be illustrated by the Evans-Buxton-Andrews spiral (Parsons, 2004; Toche et al., 2020), see Figure 23. An iterative process in which the design is becoming gradually more detailed as decisions are made, and capacities and performance of the resulting design is evaluated. Through the process an increasing amount of time and effort is put into detailing. According to Erikstad & Levander (2012) the design spiral gives a task structure of “select dimensions - evaluate capacity and performance - redesign”. They propose System-Based design for making the process more efficient. The idea is to start by describing the different components that are needed to fulfill functional requirements, for instance, how much space is needed, their weights, and how they need to be placed relative to each other. This streamlines the iterative part of the design and changes the task structure to “define systems and functions – estimate size and weight- select dimensions –check performance” (Erikstad & Levander, 2012), see Figure 24.

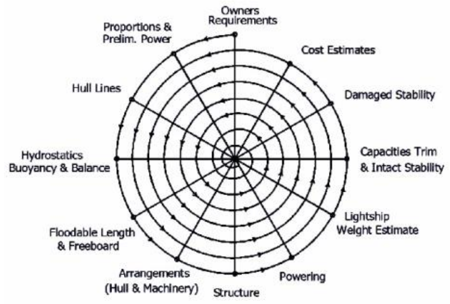

Figure 23. Point-based design, an illustration of the Evans-Buxton-Andrews design spiral. Borrowed from Naval Architecture (2014).

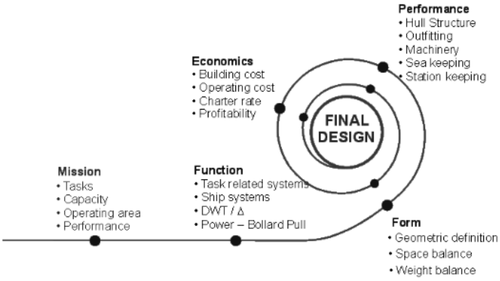

Figure 24. A modified design spiral of the System-based design approach. Figure from Erikstad & Levander (2012).

Set-based design is an alternative to point-based design, and is rather a process of converging a solution set rather than iteratively improving a single solution (Parsons, 2004; Singer et al., 2009; Toche et al., 2020), see Figure 25. Options are kept open for longer so that more information on tradeoffs is available when the decisions are made. Singer et al. (2009) describe it as allowing “more of the design effort to proceed concurrently and defers detailed specifications until tradeoffs are more fully understood”. Practical application of set-based design in vessel design can be based on three principles: “(1) consider a large number of design alternatives by understanding the design space, (2) allow specialists to consider a design from their own perspective, and (3) use the intersection between individual sets to optimize a design and establish feasibility before commitment” (Singer et al., 2009). Parametric design is an approach for using knowledge about existing designs to arrive at a set of feasible candidate solutions that can be the starting point of a further design process (Papanikolaou, 2014). Inductive reasoning is employed to establish rules on useful relations, such as typical length-width ratios of good existing designs (Coyne et al., 1990; Ebrahimi et al., 2015). Ebrahimi et al. (2015) presents the application of parametric design to offshore support vessels, with emphasis on integration of multi-variate data analysis in order to establish desired insight from available datasets (Hair Jr. et al., 2014). Appropriate pre-processing of data is also necessary, including data cleaning and assuring relevance of datapoints, for instance making sure that only data from relevant vessels is considered.

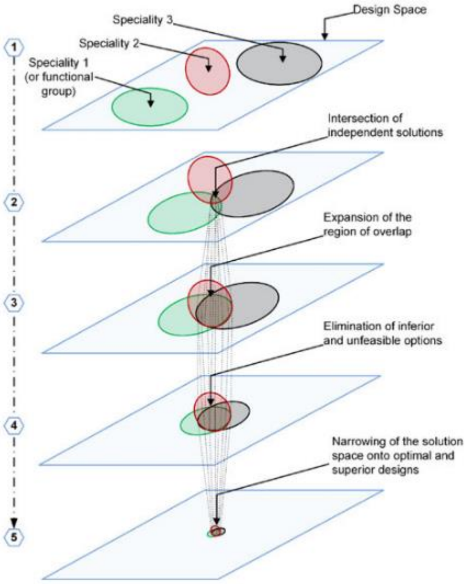

Figure 25. Set-based design as a convergence process of the feasible solution space. Figure from Toche et al. (2020).

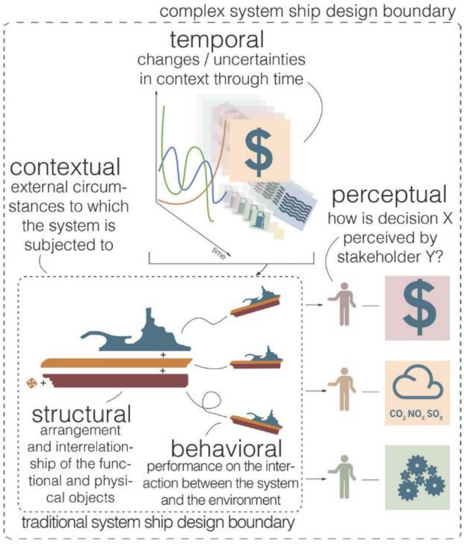

Figure 26. Five complexities of ship design, structural, behavioral, contextual, temporal, perceptual. Figure from Gaspar, Erikstad, et al. (2012).

Rhodes & Ross (2010) present five main aspects of complexity for engineering systems: structural, behavioral, contextual, temporal and perceptual, see Figure 26. Gaspar, Rhodes, et al. (2012) apply these aspects to vessel design, stating that:

"The structural aspect is related to the arrangement and interrelationship of the physical objects in the ship. (…) The behavioral aspect derives from the form-function mapping. (…) The contextual aspect covers the external circumstances to which the ship is subjected. (…) The temporal aspect relates to uncertainties in the scenarios and changes over time. (…) The perceptual aspect relates to how stakeholders perceive the value that they receive from a chosen design."

Sufficient information and adapted methods for all five aspects are necessary to establish good vessel designs.

Structural complexity can be realized through different concepts such as multipurpose, reconfigurable, and modular vessels. Multipurpose vessels are equipped to perform several different operations, while reconfigurable and modular vessels can change their configurations and thus their functionality. Aquaculture support vessels are often multipurpose due to the wide range of operations that must be performed at fish farms. The second axiom of Suh (1990) states that good designs do not include excess information or functionality. Rehn et al. (2017) investigates “tradeoffs between performance, cost and flexibility for reconfigurable offshore ships” and concludes that there are both benefits and drawbacks to designing a vessel platform to be reconfigurable. Drawbacks are mostly related to the need for “excess stability, deadweight and deck area to ensure physical compatibility” (Rehn et al., 2017). Modular design of aquaculture service vessels is studied by Nekstad (2017). A framework for designing the vessel platform is proposed, in addition to a method for “identifying systems and equipment that can be assembled into larger physical modules”. MS Frøy Fighter, a 25 m aquaculture service vessel, is used in a case study.

Behavioral, contextual, and temporal aspects relate to the suitability between the vessel and its operating environment, that is, the metocean conditions, operational profile, and market conditions that apply. Different performance measures can be used in the design process depending on the purpose of the vessel; Required Freight Rate (RFR), Ship Merit Factor (SMF), Percent operability (%OP), Operability Robustness Index (ORI), and Relative Rate of Operation (RRO) are a few examples (Gutsch et al., 2020; Parsons, 2004; Sandvik et al., 2018; Von Bock und Polach et al., 2015). Simulation-based design can provide mission related performance early in the design process, including consideration of uncertainty in metocean conditions (Bergström et al., 2016; Sandvik et al., 2018). Uncertainty in metocean conditions is a central part of the temporal aspect of complexity in the ship design process (Gaspar, Rhodes, et al., 2012). Epoch-era analysis is a scenario-based method for assessing the performance of a design in various market conditions (Gaspar, Erikstad, et al., 2012).

Operability is a measure for the fraction of time a vessel is able to operate as planned and is a function of operational limits and metocean conditions the vessel is expected to experience. In conceptual ship design it can be difficult to precisely describe future operation of a vessel, so simplifications and assumptions are made. Operational limits are commonly given as a single-parameter threshold, for example, a significant wave height of 2 m, or as a limiting sea state curve, such as a set of combinations of significant wave height and wave period, see Figure 27. A limiting sea state curve is typically based on an operational criteria, that is, a threshold for a vessel response, and thus describes all sea states that will entail vessel response that exceeds the operational criteria. Percentage operability (%OP) is a measure of the fraction of time a vessel experiences weather conditions that comply with its operational limits. %OP is commonly calculated for a “free” vessel considering only Hs-Tp by comparing the limiting sea state curve with a Hs-Tp scatter diagram (Gutsch et al., 2020). Operability robustness index (ORI) is a measure of how %OP increases for increasing operational criteria for a single response, within a maximal value. For example, how %OP increases when the limit for roll root mean square (RMS) increases from 0 to 2 degrees, see Figure 28. ORI is defined as the integral of %OP over the limit range for the operational criteria, divided by 100 times the maximal value for the operational criteria (Gutsch et al., 2020).

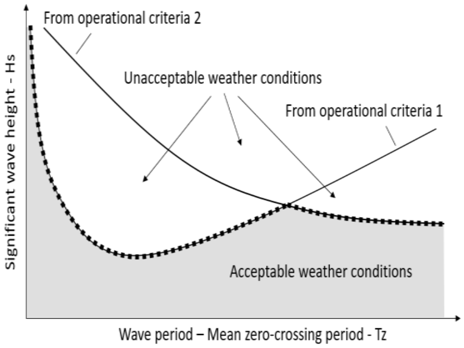

Figure 27. Two limiting sea state curves, each based on an operational criteria. The dotted line is the combined limiting sea state curve for the vessel and separates acceptable and unacceptable weather conditions.

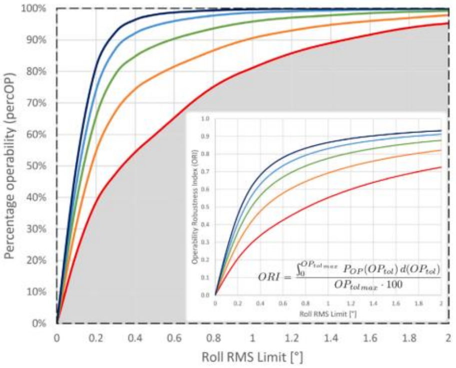

Figure 28. %OP depends on vessel design and applied operational limit. This figure from Gutsch et al. (2020) shows how %OP increases with higher limit in roll for five different vessels. ORI is integral of %OP from zero to the applied limit.

Relative rate of operation (RRO) is a measure of how many times a vessel manages to perform a mission within a given period, compared to the number of times the mission could be performed if weather effects were ignored (Sandvik et al., 2018). Vessel characteristics, operational criteria, weather data and mission information are inputs to the assessment. In contrast to %OP and IOF, RRO considers how weather develops over consecutive weather states, evaluating feasibility of missions based on required duration and weather windows. How operational limits are established is not part of the RRO method, they are simply used as input to the simulation model. A RRO score is related to the execution of a single mission type.

%OP, ORI, and RRO are often calculated for a vessel which is free in all six degrees of freedom, and the vessel behavior can be described in a wave state according to the response transfer functions of the vessel given by the hull geometry and vessel characteristics (Gutsch et al., 2016, 2020). Aquaculture support vessels often interact with fish farm structures during operations, which means that responses depend on those interaction forces. Interaction forces can include moorings, contact forces between hull and floating collar, and pull in winches or cranes. A result of the interactions is complex responses of the coupled vessel-structure system, which can lead to the need for response simulations to determine the responses. Shen et al. (2019) use simulation to assess the responses of a well-boat operating at a fish farm in waves and current.

Even though operability is a result of vessel main dimensions, hull shape, weight distribution and other vessel characteristics Gutsch et al. (2020) show that it is not necessarily true that larger vessels have higher operability. In addition, different operational limits between operations entails that operability for a multi-purpose vessel must be calculated with a relative weighing of each operation. Guachamin Acero et al. (2016) gives examples of operational limits for different activities during installation of wind turbine piles, including lowering and hammering. Placement and variations of equipment such as crane type can also affect operability, as there are independent sets of operational criteria related to the various ship-subsystems (Ghaemi & Olszewski, 2017). Finally, for modular vessels, as discussed in Nekstad (2017), vessel operability depends on the particular configuration, and is not a fixed intrinsic property of the vessel.

Useful measures for performance of aquaculture support vessels are not provided in the literature, considering the range of operations, interaction with structures, complex description of operating environment, and possibility of shared mission with other vessels. For a vessel operating completely in isolation from other vessels, functional requirements can be directly derived from the mission statement. However, if the vessel is to operate as a part of a fleet, only the functional performance of the fleet as a whole is of interest. Functional requirements for individual vessels in the fleet then result from solving the fleet composition problem.

2.2.2 Fleet composition

Aquaculture support vessels can be organized as fleets sharing the workload of serving a set of fish farms. Composing fleets to serve fish farms can then be considered a design problem where number and mix of vessels of different characteristics must be determined to achieve desired overall functional requirements necessary to match service requests. Detailed design of individual vessels is then performed to yield the desired capabilities, or, alternatively, the fleet composition can be determined based on a set of already available vessel designs. Fleet composition problems are based on the assumption that the best solution might include two or more vessels cooperating at covering one or more of the functional requirements for the fleet. This could, for instance, mean that two vessels share net cleaning operations at a set of fish farms. However, it is not necessarily the case that all vessels in the resulting solution fleet share functional requirements with other vessels. A fleet composition problem can find that the best fleet consists of vessels operating completely independent of each other.

The fleet composition problem is well known from other maritime industries such as deep- and short-sea shipping and offshore services (Hoff et al., 2010; Pantuso et al., 2014). The basic problem is a matching problem where service capacity of the vessel should match mission demand from customers. That is, the fleet of vessels should be able to perform all requested operations (Pantuso et al., 2014). Ability to perform operations can be designated as technical performance and is often balanced against economic performance which is expressed in terms of costs related to owning and operating the fleet. Technical performance is usually determined based on what vessels can do, when they can do it, and how fast, which in turn is based on vessel capabilities, capacities, operational limits, sailing speeds, and number of vessels. Economic performance depends on market prices for vessel related costs such as acquisition, fuel, crew, and profits from completed missions. Fleet composition problems vary in terms of how an operator or planner can get control of vessels. Commonly, a vessel is either owned or chartered, see Figure 29, of which the former has a higher initial cost and lower running costs. Further, charter can be sub-divided into time charter and voyage charter, also called spot charter (Pantuso et al., 2015). That is, chartering the vessel for a period and chartering the vessel for one voyage or mission, respectively. The main rationale behind composing a fleet of vessels with a mix of ownership and charter is that variations in mission demand means that there is no fleet size that is cost optimal at all times.

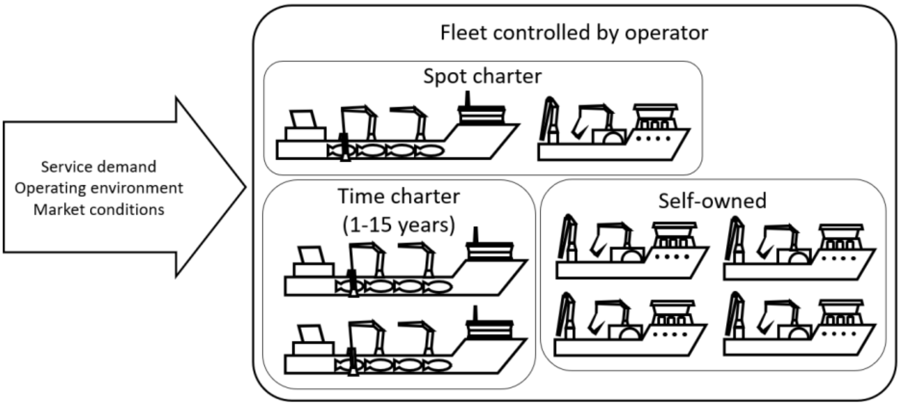

Figure 29. Fleet composition is a result of service demand, operating environment, and market conditions. A fleet can consist of both self-owned vessels and vessels chartered for different time periods, from days(spot) to years. Market conditions include price and availability of charters and cost of operation, for instance, in terms of fuel costs.

The maritime fleet size problem (MFSP) is the simplest fleet composition problem and assumes that there is only one vessel design, meaning that the only decision is to determine the number of identical vessels in the fleet (Shyshou et al., 2010). Maritime fleet size and mix problems (MFSMP) consider different types of vessels and how many to include of each type. Both MFSP and MFSMP are single-period fleet decisions, where the fleet is to be determined once and not be adjusted – thus assuming there are no significant changes in market situation or deterioration of the vessels to be adjusted for (Pantuso et al., 2014). Fleet renewal is the process of replacing vessels and adjusting fleet capacity to match perceived market development. The maritime fleet renewal problem (MFRP) is the multi-period version of the MFSMP. Pantuso et al. (2015) defines the MFRP as “the task of renewing a transportation fleet (…) choosing the number and types of vehicles to add to the fleet or dispose of in order to efficiently cope with customers' demand [and] decisions about the timing and the type of renewing actions, e.g., purchase or charter of additional vehicles"

Large investment costs, long vessel lifetime and large uncertainties separates maritime fleet composition problems from, for example, road going vehicle fleet composition problems (Pantuso et al., 2014). Market prices, demand, and weather are among the key uncertainties, and decisions are made based on current knowledge and predictions about the future (Bolstad et al., 2022). Knowledge is increased as time goes and information is revealed, however, postponing decisions can lead to higher costs and a reduced number of possibilities. For example, lead time for new builds means that new vessels must be purchased before they can be used, and availability of vessels to purchase from the secondhand market or vessels to charter is likely to be reduced in high demand periods (Pantuso et al., 2016). A consequence of waiting too long to decide can therefore be that no vessels are available for purchase or charter, and some missions cannot be performed as requested.

The three main areas for research on MFSMPs with uncertainty are shipping, offshore supply, and offshore wind farm support. While ferries and tugs are also covered in the literature, the number of publications is far lower. For shipping and offshore wind farm support demand is often considered to be the main uncertainty, to the degree that problem formulations do not cover uncertainty in weather. For offshore supply, weather is usually the main uncertainty. Considering weather is important when weather conditions affect the performance of vessels and if different vessel perform differently in weather. Both these apply in aquaculture and are in addition complicated by weather differing between fish farms, and operational limits varying between operations. Pantuso et al. (2014) covers a review of state-of-the-art literature on methods for solving fleet composition problems in maritime transportation. Only two papers were listed covering uncertainty from weather; Shyshou et al. (2010) and Halvorsen-Weare & Fagerholt (2011). Shyshou et al. (2010) covers a MFSP for offshore anchor handling tug supply vessels (AHTS) considering long-term and spot charter. Operation durations are stochastic due to weather effects, and spot rates are uncertain. A DES model is proposed for evaluating AHTS fleet size configurations, based on annual total cost. Halvorsen-Weare & Fagerholt (2011) present a voyage-based model for solving the supply vessel planning problem (SVPP), which includes a MFSMP for what supply vessels to charter. Two robustness approaches are proposed for taking weather effects into account; introducing slack and simulating candidate voyages to assess their robustness. Slack is defined as "(a) vessel's idle time after finishing a voyage before it has to start preparing for the next voyage" (Halvorsen-Weare & Fagerholt, 2011).

Fleet composition problems are usually solved as optimization problems using mathematical programs, or as a search problem using an algorithm (Pantuso et al., 2014). Mathematical programs employ an objective function, often describing a total cost or profit, and search algorithms require a model or function for ranking solutions, for instance, by determining values for total cost of solutions. For both solution methods there can be a need for considering operational details to ensure validity, avoiding simplifying the problem too much (X. Wang et al., 2018). For mathematical programs this can result in combining fleet composition and routing in the same problem (Gundegjerde et al., 2015; Stålhane, Halvorsen-Weare, et al., 2016), while for search algorithms it can be necessary to include an "operational assessment", for instance, simulating the operation of the specific fleet composition in a scenario (Shyshou et al., 2010). Use of simulation models as an integrated part of a search heuristic is extensively covered in Juan et al. (2015), including the consideration of efficient use of computational resources.

Two subcategories of mathematical programming are deterministic and stochastic programming. Deterministic programs apply if there is no uncertainty related to any information affecting what the optimal solution is. Stochastic programs are suited for solving problems with stochastic variables, for example, covering uncertainties in demand and weather. They are divided into stages where each stage reveals new information and opens for a new decision process. Two-stage models are the most common, while three-stage or multi-stage models also are frequently presented in the literature. Considering problems as stochastic requires information on probable scenarios and their probabilities, and usually provides better solutions than deterministic programs for problems where there is uncertainty. Value of stochastic solution (VSS) is a measure of how much better a solution to the stochastic problem is compared to a deterministic one, that is, the value of considering uncertainty. Solutions to stochastic problems often have value robustness meaning that the chosen solution may not be optimal for any given scenario, but rather have the best "average" outcome considering probabilities for different scenarios. This means emphasis is equally placed on not risking a total failure, as much as seeking maximal success. Value robustness is defined as "ability of a system to continue to deliver stakeholder value in [the] face of shifts in context and needs " (Ross & Rhodes, 2008), and is put in a ship design context in Gaspar et al. (2016) and Choi & Erikstad (2017). Gundegjerde et al. (2015) defines robustness of solutions as "(…) how the solutions perform when exposed to higher levels of uncertainty (…)".

Weather is a significant source of uncertainty in vessel operations in fish farming. Considering a fleet of vessels serving a set of fish farms, varying exposure level can entail large differences in simultaneous weather between fish farms. Vessel operability varies between combinations of fish farm, vessel, and operation, so MFSMPs should consider both operability and how well vessels are utilized, or in some way directly apply operational limits. There has been an increase in the number of relevant publications over the last 10 years. In the following, an overview is given of relevant papers published after 2012, with a focus on solving problems considering uncertainty in weather.

Maisiuk & Gribkovskaia (2014) solve a SVPP, which covers both fleet composition and routing and scheduling. Weather conditions affect sailing and service times. Uncertainty in weather and future spot rates are considered in a DES model that evaluates alternative fleet sizes for a homogeneous fleet. Annual vessel schedules are made by solving weekly schedules using mathematical program from Halvorsen-Weare et al. (2012). Then, the simulation is run according to the annual schedule. A lack of available vessels due to weather induced delays is compensated for by chartering additional vessels at higher rates.

Gundegjerde et al. (2015) present a three-stage stochastic program to solve MFSMP for maintenance in offshore wind. It considers uncertainty in spot rates, electricity prices, weather, and mission demand. Operations are split into activities, and each vessel type can only perform one activity type. Some operations only require one activity, but some operations require several activities and thus several different vessels. Operational limits for wave height and wind speed are considered.

Bolstad & Joshi (2016) studies “the Dual-level fleet size and mix problem for conducting maintenance at offshore wind farms (DLPOW)”. A dual-level stochastic program is proposed for determining optimal fleet size and mix, deployment, and fleet adjustments through the lifetime of the wind farm. Different heuristics are tested for solving real-life instances, including a method based on “the metaheuristic Greedy Randomized Adaptive Search Procedure (GRASP)” (Bolstad & Joshi, 2016). The problem covers different vessel types, operations, and other uncertainties in addition to weather.

Stålhane, Halvorsen-Weare, et al. (2016) presents a two-stage stochastic program to solve a MFSMP. Uncertainty is considered for weather and mission demand, and they apply operational limits for transferring personnel to turbines and for vessels staying offshore. These limits and other characteristics such as capacities vary between vessel types and determine what operations they can perform. First, weather and mission scenarios are generated. Then, all feasible maintenance patterns for vessels are established. Finally, the stochastic program is solved. A similar problem is solved in Stålhane, Vefsnmo, et al. (2016). A two-stage stochastic program is again presented for solving a MFSMP for maintenance in offshore wind, having scenarios for weather and service demand uncertainty. 50 scenarios are sufficient to get “a good level of in-sample stability, whereas out-of-sample stability requires fewer scenarios” (Stålhane, Vefsnmo, et al., 2016). One vessel has one operational limit which is related to the wave height time series, and from that the parameter “maximal operational time in hours for a vessel of type v in time period p in scenario s” is calculated. This then determines how much one vessel of that type can contribute to services.

Norstad et al. (2017) developed a simulation tool for testing vessel fleet composition, based on Gribkovskaia et al. (2016) who proposed “a methodology for quick evaluation of the feasibility and cost of the logistic system [for O&G in the arctic region] in the early stages of offshore supply planning.”. The simulation tool allows considering uncertainty in demand, impact of weather on sailing times and fuel consumption, and schedule deviations. Simulation is also used to evaluate candidate solutions in Halvorsen-Weare et al. (2017), where a metaheuristic is presented for solving MFSMP for maintenance in offshore wind. Here, uncertainty in weather and demand, that is, wind turbine failures, is considered, and direct comparison is made with the stochastic program presented in Stålhane, Halvorsen-Weare, et al. (2016). They state that the metaheuristic provides near-optimal solutions within acceptable time.

An arc-based program for solving the SVPP is proposed in Halvorsen-Weare & Fagerholt (2017). Acknowledging the significance of weather on offshore supply vessel operations solution robustness approaches are discussed, for instance, adding slack, and simulating candidate voyages to assign a robustness measure in the voyage-based model. The fleet composition method from Fagerholt & Lindstad (2000), which is based on generating feasible routes and then making schedules and thereby selecting vessels, is combined with simulation to ensure robustness with respect to weather.

Medbøen et al. (2018) proposes an optimization-simulation method for solving the MFSMP for shortsea shipping. The optimization model selects best solution based on initial parameters. Then, the solution is simulated to get validated parameter values for that solution, considering uncertainty in weather. Thereafter, the optimization model is run again with the updated parameter values, and if the same solution still is the best then it is reported as the optimal solution. Otherwise, the new solution that is found to be best is tested in the simulation model and its value is updated.

Ehlers et al. (2019) presents the Fleet Efficiency Factor (FEF) as a measure for ranking fleet compositions, defined as the relation between value of performed operations and related cost. Value is estimated based on sailing and operation times, which in turn are functions of distances, sailing speeds, effects of weather, and a weather time series. Particle swarm optimization (PSO) is used to find the best fleet according to FEF.

Amiri et al. (2019) presents a Mixed-Integer Non-Linear Programming (MINLP) model for solving an extended version of the SVPP including fleet composition, voyages, schedules, and location of onshore bases. Small and medium sized cases are solved using an exact method, while a large sized case is solved using two metaheuristics. Weather uncertainty is considered by introducing slack in idle time between voyages, which is one of the robustness measures proposed in Halvorsen-Weare & Fagerholt (2011).

Combining DES and Mixed-Integer Linear Programming (MILP) de Bittencourt et al. (2021) solves MFSP in offshore supply. Different fleet management policies and cargo allocation and delivery strategies are tested. DES allows for including weather uncertainty in the performance testing.

This section presented the problem of composing a fleet of vessels to service a demand and gave examples from the literature on how the problem is solved and, in particular, how uncertainties in weather conditions affect fleet composition. Solving the fleet composition problem for aquaculture support vessels requires consideration of a wide range of operations, and how metocean conditions at fish farms affect fleet performance. Several methods include simulation, however realistic representation of the behavior of aquaculture support vessels is not covered, and thus no sufficient method has been identified in the literature. Technical and economic performance of a fleet depends on how the fleet is used, that is, the quality of the operational decisions of fleet utilization. As recognized in the SVPP these decisions are not necessarily independent as the optimal fleet composition is affected by routing and scheduling, especially if mission information and weather forecasts are available during problem solving.

2.2.3 Fleet routing and scheduling

In addition to making decisions on what vessels to have in the fleet, there is the problem of determining how to use the vessels; what vessels that should serve each particular task, and when to do it. Ronen (1983) gives an introduction to ship routing and scheduling, in which routing is described as "specifying sequences of ports of call to ships" and scheduling is "routing with times (or time windows) attached to the calls of the ships in the ports". Routing and scheduling of ships originates from shipping, that is, transportation of cargo between ports. There are three main types of shipping: liner, industrial, and tramp (Christiansen et al., 2004). Liner means that a route is determined for the vessel and customers assign cargoes to the vessel. In industrial shipping, the cargo owner or customer is in charge of the vessel and sets routes according to their needs. Tramp resembles a taxi service, where the route is determined to maximize profits based on available missions.

The Traveling Salesman Problem (TSP) is the most basic routing problem where the central problem is to find the shortest route visiting all customers, see Figure 30. Many extensions of the TSP exist, as shown in Berbeglia et al. (2007), and the TSP can be integrated into larger solution methods (Halvorsen-Weare et al., 2012). For fleets of vessels the Vehicle Routing Problem (VRP) or the Inventory Routing Problem (IRP) is more suited to consider the number of vessels and relevant constraints on the routing solution. In the basic form VRPs cover problems of responding to customer demands using vehicles with capacity restrictions originating from a depot, see Figure 31. VRPs are popular and have wide applications, while still being an area of extensive research, as stated by Vidal et al. (2020), which also presents "existing and emerging problem variants" of the problem type. The IRP considers inventory levels at customers, with the goal of maintaining an acceptable level over time rather than delivering an exact amount at given times, see Figure 32. A potential benefit of IRP is cost savings related to freedom of choice for delivery times and amounts. However, solving maritime IRPs to ripe these benefits can be challenging (Song & Furman, 2013). Insight on customer demand from inventories is central to the problem, and the effect of distribution shape for demand on routing is studied by Soroush et al. (2020). One challenge is that standard VRP does not necessarily match maritime routing problems because "ships usually have different positions at the beginning of the planning horizon and no depot" (Pantuso et al., 2016).

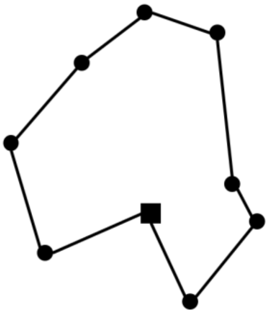

Figure 30. Traveling Salesman Problem (TSP). Shortest distance round trip visiting all customers for single vehicle.

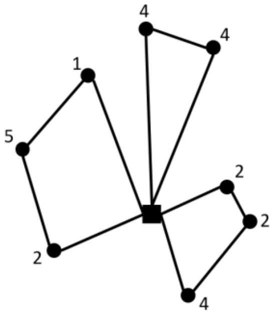

Figure 31. Vehicle Routing Problem (VRP). Vehicles delivering according to demands from customers. Routes based on vehicle capacities.

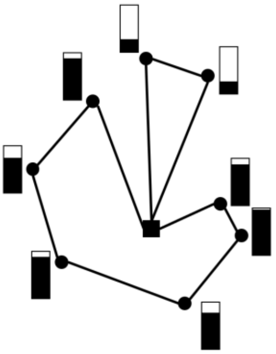

Figure 32. Inventory Routing Problem (IRP). Vehicles delivering according to inventory levels at customers. Routes based on vehicle capacities.

Even though the standard VRP and IRP are based on delivery of commodities to customers, there is no inherent difference in the problem formulation between delivering commodities and performing operations. Thus, aquaculture support vessels can be considered within the same framework of solution methods as for cargo delivery, with most operating according to industrial or tramp. In fish farming the IRP formulation is especially suitable for feed distribution because fish farms hold inventories of feed (A. Bjelland et al., 2022). VRP is more relevant for service vessel operations (Lianes et al., 2021). In the following, common extensions to the VRP are presented, with focus on relevance for the operation of aquaculture support vessels.

Time windows. If there is a time slot related to when an operation can be performed, for example, defined as the earliest and latest acceptable starting time, this time slot is referred to as a time window (Desrosiers et al., 1995). In aquaculture support operations time windows are common as it does matter when an operation is performed, not only if it is performed. An example is that some operations are not performed during night, a constraint which is studied for offshore supply services in Fagerholt & Lindstad

(2000). Penalty or reward functions can be added to time windows so that there are incentives for hitting a given time slot, while it is also possible to perform the operation in a wider period, but at a lower reward (Fagerholt, 2001). This is commonly referred to as soft time windows, as opposed to the standard hard time windows. For soft time windows there is usually also an absolute earliest and latest time, see Figure 33. If speed is variable, this can incentivize speed optimization, balancing the cost function of sailing speed with the cost function of the time windows. For instance, increasing speed and thus sailing cost in order to perform an operation before the time window closes, or more commonly, to reduce sailing speed and emissions if there is time (Norlund & Gribkovskaia, 2017).

Time-dependent sailing and operation times. Time-dependency means that durations, costs, profits, or other parameters vary depending on when sailing or operation is performed (Ulsrud et al., 2022). Typical reasons are the generation of queues at certain times, effects from weather, variations in staffing or production rates. Path flexibility can affect time-dependency of travel times, for instance, by alternative routes having less congestion at certain times or being less affected by weather (Huang et al., 2017). Weather effects are commonly described in tables form where, for example, reduction in sailing speed or percent increase in operation time is related to metocean conditions (Ehlers et al., 2019).

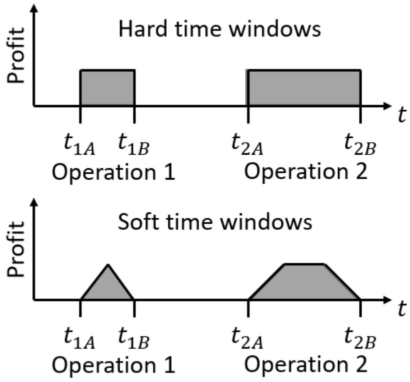

Figure 33. t_{1A} is earliest allowed starting time for operation 1. Graph shows that there are preferred times within the time windows in the case of soft time windows.

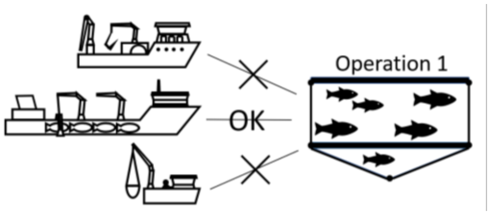

Figure 34. Compatibility requirements means that vessels must have appropriate capabilities in order to perform an operation.

Compatibility. What operations a vessel can perform depends on vessel characteristics – functionality and capacity of the vessel must match the requirements of the operation, see Figure 34. In homogeneous fleets all vessels are identical and thus interchangeable for all operations. However, for heterogenous fleets, there can be functional differences between the vessels. Multiple skill agents are, for example, service vessels that can perform several different operations. This problem extension is shared, among others, with maintenance in offshore wind. Stålhane, Hvattum, et al. (2015) considers maintenance operations at wind turbines with heterogenous fleet with respect to capabilities and different requirements for operations.

Synchronization. There can be temporal dependencies between operations or parts of an operation, thus requiring synchronization of when activities are performed. Figure 35 illustrates an operation – installing net in a pen that consists of two activities between which there is a precedence constraint, and where the second activity requires simultaneous operation of two vessels. Precedence constraint means that one activity must be performed before another can start, in this case it is necessary to transport a new net to the pen before it can be installed. Thereafter, two vessels must cooperate for the installation. These constraints can also be referred to as cargo coupling, and a version of the problem is presented in Stålhane, Andersson, et al. (2015). Coupling can also allow for two vessels to swap schedules such as described in the periodic supply vessel routing problem of Kisialiou et al. (2018b), where two identical vessels swap schedule every week to maximize utilization. The final aspect of synchronization is consolidation, that is, that the number of vessels performing the operation is irrelevant as long as the necessary capabilities are present at the same time. This means, for instance, that two less capable vessels can replace one more capable vessel in performing a specific operation.

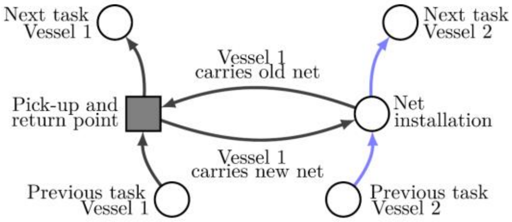

Figure 35. Precedence requires the net to be transported to the pen before installation, while the simultaneity constraint requires the two vessels to be at the pen at the same time to perform the installation. Figure borrowed from Lianes et al. (2021).

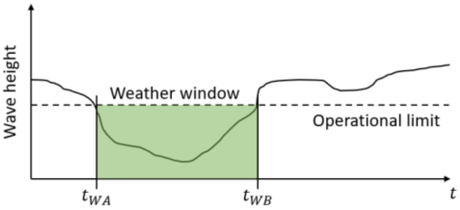

Figure 36. Combining operational limits and time series for metocean variables describes periods when operation is acceptable. These periods are referred to as weather windows. t_{WA} and t_{WB} are start and end of the weather window in the illustration, respectively.

Operational limits. Operations can only be performed when relevant metocean conditions are within their respective operational limits, giving periods of acceptable weather referred to as weather windows. Figure 34, shows an example for wave height. Operational limits for several different metocean variables may apply, and they are dependent on vessel and operation. Combining weather windows and time windows determine when operations can be performed. Since there is uncertainty related to weather forecasts, this also affects establishing weather windows in planning. If a problem is formulated as deterministic, weather windows can be considered in preprocessing and thus integrated into time windows, as done in Stålhane, Hvattum, et al. (2015). However, for stochastic problems other approaches are necessary. Operations often have an expected duration and are not initiated unless weather windows are long enough (Ren et al., 2019). In marine operations an alpha factor is often used to determine if operations should be initiated based on weather forecasts, considering uncertainty (DNV, 2011). In short, depending on expected duration of operation and limiting wave height, an alpha-factor between 0 and 1 is selected according to a table. If forecasted wave height exceeds the product of the alpha-factor and limiting wave height, the operation is not initiated.

Routing problems are commonly solved for short periods, for example, days due to stochastic elements. However, the underlying problem is long-term, or multi-period by nature, meaning that new plans must be made continuously. Solving the routing problem again at a later time entails that new information might have been revealed and that one or more operations might have been performed, while others remain from the previous problem. A rolling horizon framework can be used to solve a series of short-term problems (Branda et al., 2017; Fernández Cuesta et al., 2018). If the original plan turned out not to work, re-routing or the application of some ship scheduling recovery strategy is necessary. Elmi et al. (2022) review such recovery strategies for responding to disruptive events in liner shipping. These events are often related to inherent uncertainty in weather conditions and operation times, that is, weather being rougher than expected, or operations taking longer than planned. Berle et al. (2013) assess vulnerability of a maritime LNG transportation with respect to risks for disruption, for instance a vessel needing unexpected repair or an operation taking significantly longer than anticipated. A formal method is presented for quantifying "disruption costs and cost/efficiency of mitigating measures" (Berle et al., 2013).

Solution robustness is typically valued in addition to costs, profits, or other measures. Robustness is related to the likelihood that the requested operations will be performed within their time windows even if weather conditions can change or if there are sudden additional operations. Halvorsen-Weare & Fagerholt (2011) and Halvorsen-Weare & Fagerholt (2017) investigates approaches for creating robust schedules for offshore supply vessels, for example, by adding slack. Norlund et al. (2015) balances cost, emissions and robustness when solving a vessel speed optimization problem using a combination of simulation and optimization. This is followed up by a method for improved estimates on fuel consumption for schedules by simulating different weather scenarios (Norlund & Gribkovskaia, 2017). Kisialiou et al. (2018a) presents a method combining ALNS and DES for solving the SVPP considering the tradeoff between cost and service level in rough weather, while Kisialiou et al. (2019) use a similar approach to solve for uncertain demands.

Solution robustness and recovery strategies or contingency plans are especially important in fish farming because most operations have a direct impact on fish welfare. Time windows and need for operations are not set solely from an economic objective or customer requirements, often it is related to the wellbeing of living creatures - maintaining a good environment for the fish or direct treatments of fish. Examples are cleaning of net to improve water flow through the pen, which is important for oxygen and nutrition levels, and delousing fish or collection of PD infected salmon. Planning should therefore, to the extent possible, maximize likelihood that operations are performed within requested time windows, and strategies should be in place for replanning if needed.

No papers were identified in the literature that cover all main aspects of aquaculture support vessel routing and scheduling. Thus, this is identified as a research gap. In addition to fleet composition and routing and scheduling of the vessels, sudden needs can arise that require vessels to redirect their efforts, for instance, taking a role as an emergency response resource. This topic is covered in the next section.

2.3 Unwanted events

History has shown that things do not always go as planned, and that there is a benefit related to considering possible unwanted events. This also applies to fish farming. Unwanted events can occur either because of human error, faults in design, planning, or force majeure. This can include man over board, heeling of a fish farm, machinery breakdowns, or algae blooms (Danielsen, 2019; FishFarmingExpert (Eds.), 2021). Accidents, human injuries and fatalities are also parts of the picture, and aquaculture has been found to be the second most dangerous workplace in Norway (Holen et al., 2018a, 2018b). A large project for offshore fish farming, called Smart Fish Farm, covers the following ten hazards and accidents in their emergency preparedness analysis: (1) Serious personal injury or acute illness, (2) Fire on board, (3) Structural damage, (4) Collision, (5) Loss of position, (6) Fish escape, (7) Loss of fish health, (8) Extreme weather, (9) Missing personnel, (10) Uncontrolled release of potentially environmentally harmful substances (SalMar ASA, 2021). There is significant uncertainty related to the probability of occurrence and consequences of unwanted events, representing more or less quantifiable risks related to operation of fish farms. The emergency preparedness analysis related to Smart Fish Farm only covers a qualitative method for identifying reasonable needs and expectations for response performance (SalMar ASA, 2021).

Risk is the combination of probability and severity, often given as the product of the two, or as defined by Rausand (2011): “The combined answer to three questions: (1)

What can go wrong? (2) What is the likelihood of that happening? and (3) What are the consequences?”. Risk assessment and determination of what measures to implement to avoid and minimize consequences of events, is often based on perceived probability and severity unless there are rules and regulations determining a minimum level for prevention or preparedness. In risk assessment, a terminology is established to enable evaluation of series of events and how they together can lead to a final outcome, depending on relevant barriers and how the final outcome depends on various events. A popular representation in risk assessment is the bowtie model, see Figure 37. Hazards lead to an accidental event which in turn entails consequences (Rausand, 2011). Barrier controls and escalation controls can prevent the accidental event from occurring, and preparedness in terms of mitigation controls and recovery controls can reduce consequences of an accidental event. Figure 37 shows two examples of accidental events in fish farming, with related hazards, prevention measures, preparedness measures, and consequences.

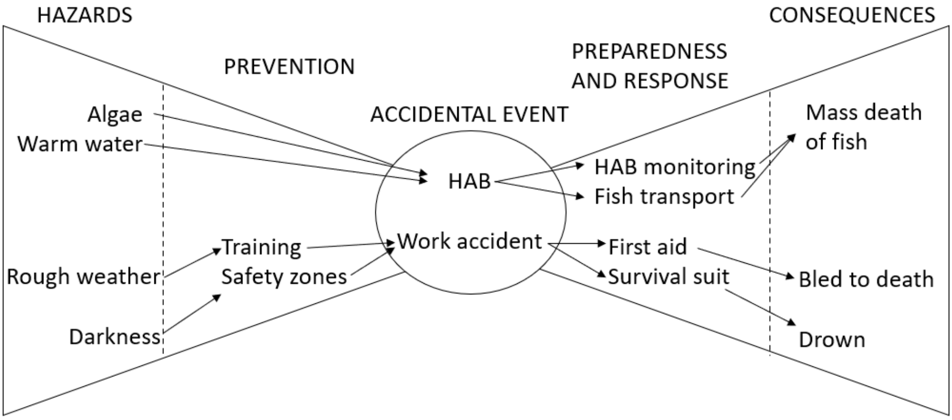

Figure 37. Bow-tie model illustrating the relation between hazards, accidental events, and consequences. Prevention measures can reduce probability or severity of accidental events, and preparedness and response help to reduce or avoid consequences. The figure is a contextual adaptation of a general model that can be found, for instance, in Rausand (2011). HAB – Harmful Algal Bloom.

This means that prevention and preparedness can reduce both probability and consequence of events. A key principle in risk management states that risk should be As Low As Reasonably Practicable (ALARP) (Health and Safety Executive, 2022). ALARP includes a cost-benefit analysis of risk reduction measures, and thus establishes a rational behind what measures to implement. A prerequisite is availability of methods and information to properly assess costs and benefits of risk reduction measures. With expansion of the aquaculture industry into more exposed and remote areas, it can be expected that more of the responsibility for emergency preparedness and response is shifted from public services to fish farmers, and that requirements for documenting emergency preparedness will become more comprehensive. In the proposal for new regulations on offshore fish farming in Norway, it is stated that “distance to land and to existing infrastructure and preparedness means that it is necessary to increase requirements regarding personnel safety and location specific preparedness for offshore aquaculture facilities” (Norwegian Ministry of Trade Industry and Fisheries, 2022). Further, requirements are formulated regarding documentation of preparedness and ability to respond quickly to emergencies related to fish health and fish welfare. This entails significant incentives for precise methods for assessing both prevention and preparedness measures. In Section 2.3.1 and 2.3.2, prevention and preparedness are discussed, respectively. Focus is on the more common and severe events, such as human injuries and casualties, and loss of biomass. Most often, the objective is to avoid occurrence of accidental events by implementing preparedness measures. However, this is not always possible, and measures may not be successful. Therefore, preparedness is also necessary, and in some cases the only practical approach for minimizing consequences. For instance, preventing HABs is practically impossible, so preparedness and response determine the consequences.

2.3.1 Incident prevention and safety

Studies on accidents at sea has shown that the majority is related to human factors (Rumawas, 2016). Design, perception of safety climate, planning of operations, and training are important factors in determining the risk for accidents. Kongsvik et al. (2018) found that safety is not always the top priority and that employees’ perception of safety climate and importance of compliance with rules varies. Safety climate might also have an effect on reporting of hazardous events, which in turn is crucial for learning to reduce risk of similar events in the future (Kongsvik et al., 2019).

Rules and regulations are based on experience from hazardous events and represent a minimum requirement for prevention. Relevant regulations in Norway include: Regulation on technical requirements to floating aquaculture plants (NYTEK-forskriften, 2011; NYTEK23, 2022), regulation on construction and inspection of smaller cargo vessels (Forskrift om bygging mv. av mindre lasteskip, 2015), and Ship safety and security act (Skipssikkerhetsloven, 2015). Company policy and freedom for crew to make independent assessments of risk in each situation are necessary additions to provide improved safety in each particular instance. Operational limits are typically based on human endurance, that is, how performance is affected by operating conditions (North Atlantic Treaty Organization, 2000). However, the resulting safety level depends on level of training and perceived safety culture and compliance. Insufficient tools for training of fish farm operators to cope with demanding operations led Holmen, Thorvaldsen, et al. (2017) to investigate the development of a suitable simulator training platform. Kongsvik et al. (2018) investigates how perceived pressure to perform can lead to crew initiating operations even if metocean conditions are too harsh, or in other ways safety is not satisfactorily maintained.

Prevention seldom guarantees a zero probability of occurrence for a hazardous event, and preparedness measures can thus still be beneficial. For certain events, such as HABs or storms, prevention may not be practicable, and more effort have to be placed into preparedness.

2.3.2 Emergency preparedness and response

Emergency preparedness covers preparation for needs that are expected to arise with high priority and urgency, but for which the time of occurrence is uncertain. There are various regulations related to emergency preparedness today, such as Akvakulturdriftsforskriften (2008), Arbeidsmiljøloven (2005), Forskrift om brannforebygging (2015), Forskrift om utførelse av arbeid (2011), and Forurensningsloven (1981). In brief, these cover emergency plans, responsibility regarding contamination, obligation to notify, and risk of fire. Implemented preparedness measures are based on a compromise between probability of occurrence, expected outcome and cost of measures. Outcome is the combination of direct and indirect consequences, and how they are perceived by various stakeholders, for instance decision maker and authorities, in terms of life, environment, and assets. Costs can be related to inventory of relevant resources and equipment, training of personnel, and loss of income from redirecting resources in operation to emergency response. Probability of events can change with time, leading to a heightened or lowered preparedness depending on the perception of decision makers. Before the algae bloom in northern Norway in 2019 it had been long since the previous bloom, and at that time the industry was significantly smaller. Following the 2019 algae bloom, and recent blooms in Chile, the benefit of early warning has been discussed, and research projects have been initiated (Davidson et al., 2021; Mowat & Chadwik, 2021). For some types of unwanted events, the probability and potential severity can be estimated based on variables that can be easily monitored, thus supporting a dynamic approach to preparedness. For instance, rough weather entails higher risk of structural failure and fish escapes, and the metocean conditions leading to HABs are well known (Davidson et al., 2021; Mardones et al., 2021). It makes sense to increase preparedness in such situations. Expectations for consequences of events impact decisions on preparedness and should ideally be based on accurate estimates of true consequences. For all types of situations that require emergency response, it is valuable to know as much as possible about the response performance. This is necessary in order to assess if current safety levels are acceptable or not. Not knowing or not trusting estimates on consequences of emergencies invalidates decisions on correctness of risk reduction measures.

Relevant literature on preparedness assessment in maritime applications mostly relate to oil spills. Traditionally, experience has been used to evaluate emergency preparedness, comparing available resources with expectations for needs. This could be either through rules for minimum response capabilities and equipment, or through expert judgement (Haixiang et al., 2017; Y. Wang et al., 2018). Omorodion et al. (2021) integrates expert opinion into a Fuzzy Analytical Hierarchy Process (FAHP) for assessing “ERRV safety in offshore emergency response operations”, also introducing the aspect of risk of Emergency Response and Rescue Vessel (ERRV) failure during rescue operations.

A different approach is to model and investigate development and outcome of emergency scenarios, so that the relation between preparedness and consequence is evaluated objectively. B. Li et al. (2021) presents a method for predicting emergency scenarios by combining historical accident data and machine learning – a useful prerequisite for scenario testing. GIS based methods are used in maritime emergency response and rescue to estimate response times (Siljander et al., 2015). A three-step framework for evaluating the capability of maritime search and rescue (SAR) services is presented in Zhou et al. (2020). Step 1 uses GIS to determine response times, step 2 establishes demand, and step 3 quantifies the capability of the SAR. Berle et al. (2013), Bergström et al. (2014) and Brachner (2015) use simulation models to determine system performance. Bergström et al. (2014) design a robust arctic maritime transportation system by evaluating system performance in various ice conditions and using different ice mitigation strategies. A model for evaluating response capacity is presented in Brachner (2015) where rescue following helicopter ditches is considered. The study covers events in the Barents Sea, with one year of varying weather conditions, and different configurations for positioning of response units.

Fleet deployment and scheduling determine emergency response capability. Positioning of rescue vessels to achieve maximal coverage is a central problem for minimizing response times, and is solved for different scenarios by combining mathematical programming and epoch-era analysis in Pettersen et al. (2019). Scheduling of emergency resources in active emergency response is studied in Y. Zhou et al. (2017) where a multi-objective evolutionary algorithm (MOEA) is proposed as a solution method for optimizing use of resources. Response routing of resources is similar to normal routing, but the twist is to determine what vessels should respond and when to do so in order to minimize effect on normal operations while minimizing consequences of the emergency event. Brachner et al. (2019) present models for optimizing emergency response systems for helicopter ditches in offshore oil and gas. They find that response time, both average and maximum times, and response capacity are useful performance metrics for emergency response systems (ERS). Extensive discussion on optimal SAR planning problems are covered, and three different mathematical problems are developed in Feldens Ferrari (2019). In another study, Pettersen et al. (2020) takes a different approach to emergency response and what constitutes the ERS by investigating latent capabilities in vessels, and how those can facilitate emergency response contributions. That is, how vessels not necessarily intended to have a role in emergency response can turn out to be valuable resources. The case study of Pettersen et al. (2020) is based on the Macondo oil spill, but repurposing assets in emergencies can be useful also in fish farming. An example is the use of well-boats for moving fish during the HAB in Chile in 2021, however there is no literature on that specific application (FishFarmingExpert (Eds.), 2021).

Typical major hazardous events in fish farming that can call for emergency response are fish welfare related, such as escapes, HABs, oil spills, jellyfish invasions, and severe cases of winter ulcer or other diseases (Slette et al., 2022). These can require rapid transportation or euthanasia of large numbers of fish (FishFarmingExpert (Eds.), 2021). In such cases preparedness covers availability of relevant resources, plans for execution and efficient organization of necessary responses at short notice. Reponses to fish welfare emergencies requiring transportation or euthanasia of large numbers of fish will necessitate several visits from vessels.

Current preparedness strategies in aquaculture are based on utilizing aquaculture support vessels that participate in normal operations as emergency response resources, without any specific emergency response infrastructure. Strategies commonly also cover agreements between companies to share vessels if necessary. This “double” role of the vessels makes it difficult to assess the preparedness as it depends on the willingness of decision makers to direct vessels to response efforts, possibly having negative effects on normal operations. It also makes response planning challenging as position and status of vessels constantly changes in normal operation. Events affecting more than one fish farm in an area, which should be expected for instance for HABs or storms, will also entail an overload of the preparedness compared to the strategy – leading to queues. An order of priority is then necessary, and this can mean that there are fish farms without real preparedness in case of certain events. For instance, in a sudden and severe HAB, response time is critical and being placed far back in a queue can be equivalent to not having any response because the fish will be lost before resources arrive.

Crisis management is another important topic. Large scale responses can require involvement of decision makers at different levels, as seen after the algae bloom in Norway in 2019 where many companies in a large area were affected. Authorities took lead on handling the situation and coordinated efforts from several agencies including Directorate of Fisheries, Food Authorities, Institute of Marine Research, and Norwegian Veterinary Institute (Marthinussen et al., 2020). In these situations, good information flow and coordination of activities is a critical (Andreassen et al., 2020; Kristiansen et al., 2017).

An identified research gap is the lack of methods for assessing emergency preparedness in terms of quantifying consequences for events relevant for fish farming. Especially considering types for large fish welfare emergencies requiring several visits, and use of non-dedicated resources. Methods from O&G are valuable to study as a basis for what can be developed for aquaculture due to the extensive research on the area in O&G, and similarities between the industries. Safety of personnel, harm to the environment, and damage to assets are central concerns in both industries. However, there are significant differences both because the commodity in fish farming is a living creature, and the profits margins have historically been much lower.

2.4 Sources and timeline of literature review

This review covers literature from different research fields relevant for the design and operation of a fleet of aquaculture support vessels. From describing the environment in which the vessels operate, to methods for considering particular operational constraints in solution generation. Literature from operations research and marine design are most cited, in addition to metocean and safety science. A total of 234 references are cited from scientific journals and other sources like books, laws and regulations, reports, and theses. An overview of the ten most cited journals is presented in Table 2 to give an impression of diversity in terms of topics and journals. It is worth noting only 53 research papers are covered by the ten most cited journals. Figure 38 shows when all references were published.

Table 2. Overview of the 10 most cited journals and the number of cited references per journal.

Journal	**No. of papers**
Ocean Engineering	9
European Journal of Operational Research	7
Transportation Research	6
Aquaculture	6
ASME - Offshore Mechanics and Arctic Engineering	6
Aquaculture Environment Interactions	5
Applied Ocean Research	4
Computers and Operations Research	4
Aquaculture International	3
Aquacultural Engineering	3
Sum	53

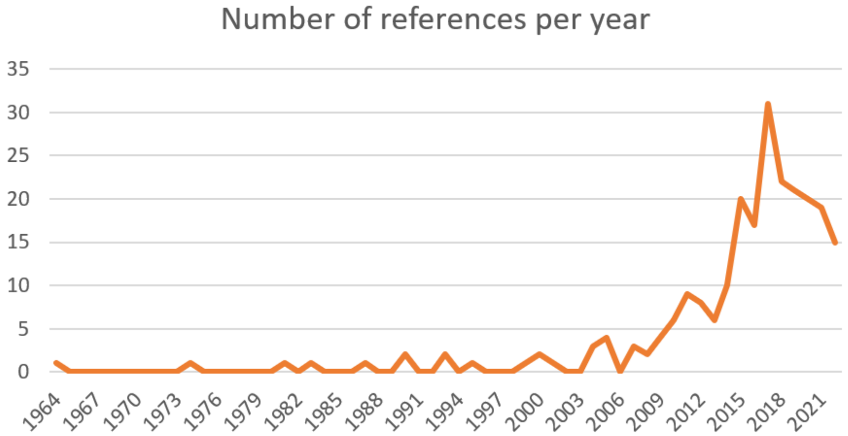

Figure 38. Number of references per publication year. Most of the cited research is published in the last 10 years. 2017 is the top year with 31 references.

The presented review is considered to be of sufficient scope with respect to topics and relevance of references for presenting background and research gaps that cover the basis for this research project. Achieving high vessel fleet performance in fish farming relies on an understanding of the operational environment, cooperation between vessels in a fleet, relation between strategic and operational considerations, and roles of vessels both in routine and emergency operations. Two major aspects of the operational environment are the number of fish farms in terms of demand complexity and geographical spread, and differences in metocean conditions between farms, from sheltered to exposed.

Identified and highlighted research gaps cover consideration of availability for vessel operations in site selection for fish farms, methods for routing and scheduling adapted to realistic problem formulation for utilization of aquaculture service vessels, and methods for assessing quality of ERS with respect to outcomes of emergencies. In general there is a lack of understanding of how metocean conditions affect the performance of fleets of aquaculture support vessels serving groups of fish farms with variation in metocean exposure.

3 Research approach

A presentation of the research approach is given in this chapter. First, the research question is revisited, and the context of the research study is described. Thereafter, research type is discussed before research methodology is covered in Section 3.1 and research methods in Section 3.2. Describing research type is a categorization of what branches of research the methodology belongs to, while the methodology itself is a description of how the general approach taken in carrying out the research project (Leedy & Ormrod, 2015). Methods are chosen to detail specific steps of the methodology, based on particular considerations of the problem, project boundaries, and context.

Answering the research question is the sole objective of a research study. Consequently, how research is conducted should be a result of considerations on how to maximize generation of useful insight with respect to the research question. Revisiting the research question, as stated in Chapter 1:

> *"How can design of and operations planning for aquaculture support vessels provide available and safe vessel operations at exposed fish farms?"*

A research question can be approached in many different ways, both because different stakeholder may have different perceptions of what the research gap is, and the context in which it is raised sets conditions for how it is solved. Research design seeks efficient utilization of available funds and other constraints given by project boundaries, for example, in terms of available competence. Research approach and strategic decisions thus depend on how key stakeholders perceive the nature of the problem, and their subjective beliefs of how different approaches can contribute to generate the desired knowledge. The researcher's experience and the audience of the study also play a role in what are considered valid assumptions and appropriate methods for "data collection, analysis, and interpretation" (Creswell 2014). Context of this research study is given by participation in SFI EXPOSED, a center for research-based innovation on exposed aquaculture operations, and in the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). A choice was made to study the technical aspect of the research question, and to comply with the objective of the center to facilitate innovation in the aquaculture industry.

According to Kothari (2004), research can be divided into the following main classifications: Descriptive vs. Analytical, Applied vs Fundamental, Quantitative vs Qualitative, and Conceptual vs Empirical. In addition, there are further classifications that can be added.

Research approach

In descriptive research, the goal is to gather information on the current state of a system, while analytical research deals with critical analysis of data. Information gathering is not central to this project as this is largely provided by SFI EXPOSED and through its project partners. It is the analysis of data, and what further insight that can be deducted through assessments and modelling that is of interest. Hence, this research is **analytical**.

Applied research relates to "immediate problem(s) facing society or an industrial/business organization" (Kothari, 2004). Fundamental research covers the other end of the spectrum in observing and understanding basic principles and relations that can be utilized in further research "without prior consideration that it will result in any practical application or use" (Fondation Synergie Lyon Cancer, 2013). SFI EXPOSED is a center for research-based innovation, and as a part of which this project is concerned with application of results to enable businesses to tackle immediate challenges they face. Hence, this is **applied research.**

While quantitative research focuses on the "what", qualitative research focuses on the "why" (Ahmad et al., 2019). The former employs numeric data and statistical analysis to establish objective truths, while the latter establishes subjective understanding from "non-structured techniques like in-depth interviews, group discussions, etc." (Ahmad et al., 2019). Both approaches could be applied to answer different interpretations of the research question, however quantitative is most appropriate to gain desired knowledge on what relations exist and how to adapt to them. This is opposed to understanding why things are the way they are. Hence, this research is **quantitative**.

A **mix of conceptual and empirical research** is applied. Based on loose, initial hypotheses about probable causal relations relevant for the research question, the goal is to arrive at conclusions verifying or refuting these based on empirical research. That is, generating new, necessary information from available data through testing. Arguably, the research is also conceptual because it required formulation of new measures for interpreting behavior of the analyzed system and understanding characteristics of design and operation.

Quantitative research can be sub-classified into inferential, experimental and simulation approaches (Kothari, 2004). Inferential means to predict or estimate generalized knowledge based on available (non-exhaustive) information, for instance, infer rules for behavior of aquaculture support vessels based on descriptive information about a sample. An experimental approach would cover controlled testing to establish data on specific system configurations and scenarios, allowing for analysis of effects of variations in input variables. Simulation is an alternative to physical experiments in the sense that it provides the same possibilities for testing. A significant difference is that behavior is modelled according to the "designer's" perception of the real-world system. This means that simulation models always are imperfect representations of the real system, and simulations are thus imperfect imitations. However, lack of accuracy may be acceptable considering the benefits in terms of testing time and control of variables. The **simulation approach** was chosen because of the combination of practicality for testing of the systems in question and the possibility for testing for exactly the desired sets of inputs. Experiments would be prohibitively expensive and time consuming, and relevant input variables such as metocean and market conditions are difficult or impossible to control.

In addition to the main classifications of Kothari (2004) the research study can be characterized as **decision-oriented and predictive**. Decision-oriented as opposed to conclusion-oriented because insight on the topic of the research question is needed as support in decision making. Operations research is decision-oriented and was widely applied in the research study for gaining knowledge on operational and planning problems related to the research question. Predictive research covers the search for knowledge on prediction and forecast of behavior and future values which can be related to evaluation of specific courses of action (American Psychological Association, 2022). This is closely related to both decision-oriented research and empirical research, while being in opposition to explanatory research which is concerned with assessing why “a particular finding occurred” (American Psychological Association, 2022).

3.1 Research methodology

Research methodology is the “general approach a researcher takes in carrying out a research project” (Leedy, 2015). In other words, research methodology of a research project describes how the research was conducted. It is up to the researcher to design a methodology they think is appropriate in achieving research objectives and gaining insight on the research question. There should be a high “likelihood that [the methodology] will yield accurate, meaningful, and credible results” with respect to the research question (Leedy & Ormrod, 2015). Design and selection of methodology is not an exact science and is also a result of the context in which the research project is carried out and practical limitations that apply. In addition, with the progression of the project, as new insight is attained, both research question and research methodology may at some stage be found to no longer seem as relevant or appropriate. In which case, either the methodology is revised and changed, or research is simply conducted and finalized as planned, if possible. A methodology should cover collection of necessary information, how to apply that to generate valid results, and interpretation of those results to get valid conclusions. Describing research methodology and making it available for other researchers is an important principle of the scientific method, because it is a necessity for rigorous, critical evaluation of validity of findings and reproducibility of results (Kothari, 2004).

The research methodology applied in this project is designed to enable decision makers to establish causal relations between input variables to a fleet system and various performance estimates. Hence, it can be described as causal research, deducting relations between input variables describing a system configuration, and outputs in terms of performance measures. This is illustrated in Figure 39, where scenario information covers a complete description of relevant system variables, and performance estimates covers any metric of interest that can be deducted based on input information. Figure 39 illustrates three possible approaches for generating predictions on outputs, judgmental forecasting, historical data or time-series analysis, and simulation. That is, for instance if a stakeholder is to evaluate a vessel design with respect to a given context or scenario, there are several ways in which this can be done.

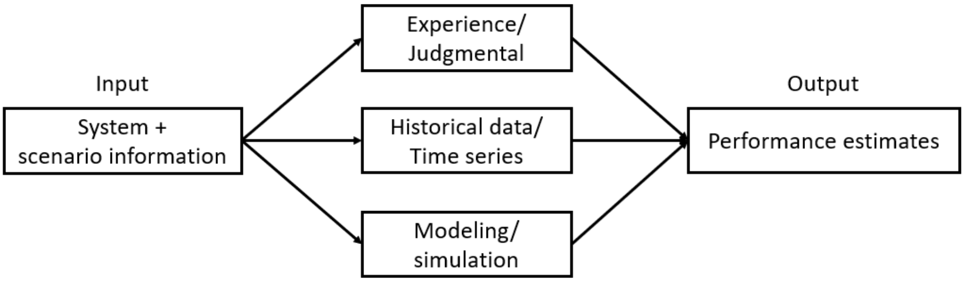

Figure 39. Several approaches can be used to predict performance of a system design in a scenario. Three possible approaches are experience or judgmental forecasting, historical or time-series analysis, and modeling or simulation. An example case is predicting some performance metric for a vessel design in an operational scenario. Modeling is the chosen approach in this research project.

Judgmental forecasting, or experience-based, equates to assuming relations based on practices or rules of individual stakeholders, and how they would act or how they believe causal dependencies would be in each scenario (Lawrence et al., 2006). For judgmental forecasting to be accurate, the forecaster must have good domain knowledge and be well informed (Hyndman & Athanasopoulos, 2018). Historical data can be used to statistically describe relations based on scenarios that have occurred, possibly allowing for accurate prediction of performance from similar scenarios given the fidelity in the description of the scenarios (Hyndman & Athanasopoulos, 2018). That is, assuming known datasets hold enough information, for example, on variations in input variables to establish some estimate on dependence functions for all relevant variables. This approach is commonly used in analysis of metocean conditions as presented in Section 2.1 and depends on the assumption that historical data can say something about future behavior. Simulation is the chosen approach in this research project because it allows employing generic, validated principles or characteristics for behavior of components, into an aggregated model for which new scenarios can be tested. Hence, allowing for analysis of scenarios for which there is no relevant experience or historical data available. This is relevant for this project considering application of the model in novel system design. As opposed to experience, models provide an objectivity and consistency in the results they generate. Such models must be made according to desired performance estimates. That is, for a model to be useful, it must be adapted to provide the desired outputs.

Investigating causal relations may require construction of suited models, which in turn necessitates an understanding of system behavior and how decisions in modeling and experiment setup can affect validity of the results. Construction of models representing systems that do not exist builds on characterizing behavior of existing system components and their combination into new systems. Models comprise not only representations of physical objects, but also “processes” such as routing strategies. The research methodology consists of three steps; understanding, modeling, and investigating described systems, see Figure 40. This includes collection and interpretation of information to understand the behavior of the real-world system, both to model it well, to determine what inputs to test for, and to analyze results in a useful manner. Modeling was used iteratively to learn and understand behavior through validation with information on real-world systems. Due to lack of useful datasets for validation of the models, focus was on verification of sub-components and investigation of selected scenarios. Hopefully, demonstration of useful methods and models for application of such datasets will motivate stakeholders to collect relevant information enabling better validation in the future.

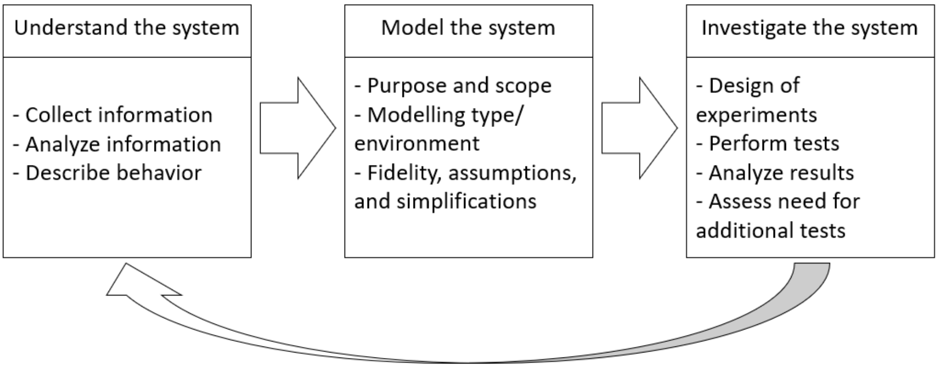

Figure 40. Description of the research methodology - investigating systems by using modeling to imitate behavior. New insight is gained from investigating system characteristics in terms of relations between input and output parameters of the modeled system. This requires good understanding of the system and smart modeling weighing practical limitations and accuracy.

3.1.1 Understanding system behavior

Understanding the system means both to gain knowledge on behavior of existing system configurations, and what alternative, novel systems could be in terms of changes in physical composition or processes. Several methods were applied including literature review, data collection, interview of stakeholders, discussions with colleagues and at conferences, and field trips with observation. Both qualitative and quantitative research methods were applied. Qualitative to understand procedures, mechanisms, perception of situations, decision making, and what considerations were made in different situations. This was important when trying to model and imitate the system. For example, realizing the number of factors determining if and when a vessel can perform an operation at a location, from the operation practice, vessel functions, and design of the fish farm to weather conditions, competence and risk perception of the crew, and strategical decisions. Quantitative methods have also been crucial in understanding systems, for instance, in establishing probabilities for different events, sea states, or operations requests, and other numerical characterizations. Data collection for this thesis was largely dependent on access to industry through participation in SFI EXPOSED. Little data is available on complete relations, that is, logged input and output of the extent that describes system states. Thus, information gathering was more directed towards understanding the “rules” of the behavior and how they can be integrated in modeling.

An initial literature review was performed on topics of fish farming, metocean, vessel design and routing, and what affects decisions on vessel fleet composition and vessel operations. This is not only about understanding the current fish farming system, but also mapping state of the art on relevant topics that can be applied in a fish farming context with respect to the research objectives. In particular, this meant including literature on use of operations research and simulation to design and operate fleets of vessels in fish farming and identifying research gaps within the research question.

Data collection was mainly achieved through participation in SFI EXPOSED. The center collects joint datasets on metocean conditions from weather buoys at partner fish farm locations, motion data from inertial measurement units (IMU) on vessels, and logs of operational decisions related to perception of weather conditions and risk. This information was reviewed and analyzed to form an understanding of the behavior – attempting to establish rules for correlation between variables such as weather conditions, and decision making or perception of the weather. SFI EXPOSED also provided some data on vessel types and their characteristics, operation types with typical associated request frequencies and equipment required to perform them, as well as examples of operational limits from industry partners. However, the information was not extensive and insight from literature reviews, interviews and observations in field trips were needed to gain a sufficiently broad impression of general state of the industry and practices. For example, after visiting one vessel or talking with one captain it is easy to assume that all the extracted information applies to all cases in the industry, however after visiting another vessel or talking with another captain, it becomes evident that it is not the case. In exploring this diversity, at some point a notion materializes on what is normal and what the variations are.

Stakeholder interviews was one way of supplementing the initial information collected from literature reviews and from SFI EXPOSED. To understand decision making processes, for instance, on routing, further details were needed to be explained on consideration of weather conditions with respect to operational limits. Most interview were made during field trip on vessels or at fish farms, during gatherings in SFI EXPOSED, and by phone calls. Interview subjects included personnel at fish farms, on board vessels and planners and decision makers. Interviews were often based on already attained knowledge from other sources and were not structured but rather dynamically adapted to interview context, and knowledge and practices of the subject. As the research project progressed, it became clear that valuable discussions could arise unexpectedly. Therefore, a general template was made with questions and topics that was especially relevant for the project at any given time, so that semi-structured interviews could be performed when opportunities arose. For example, when traveling with a well-boat and it stops at a fish farm to perform an operation, personnel at the fish farm often comes up to the bridge to talk with the well-boat crew, possibly opening for valuable conversations from a researcher's perspective.

Model drafts and hypotheses for system behavior were made based on preliminary understanding, and they were discussed with colleagues and with peers at conferences and gatherings. Efforts were made to construct a DES model of the complete system to reveal knowledge gaps and uncertainties in component behavior. Models and hypotheses were presented at industry relevant conferences such as DNV-GL Nordic Maritime Universities Workshop, NTNU Ocean Week, AquaNor, TEKNA events, The International Maritime and Port Technology and Development Conference (MTEC), and center gatherings in SFI EXPOSED.

Three field trips were made as part of the research project; a 10-day trip with a multi-purpose service vessel, a 7-day stay at a fish farm, and a 2-day trip with a well-boat. The 10 days on a service vessel were spent onboard 27-metre MS Multi Safety of FSV in northern Norway, experiencing the lifestyle, different weather conditions, long sailing legs, and operations at fish farms. Most of the time was spent inspecting a fish farm, with an ROV traveling the full length of each of the more than 30 mooring lines, and coupling plates being lifted onboard to be sprayed clean and checked. Other operations included transport of fuel and water to a fish farm and moving a pen within a fish farm. Fortunately, the bridge has an undisturbed view of everything happening on deck making it possible to observe everything, and the crew were welcoming and open to share their thoughts and experiences. The seven days at a fish farm were spent at Mowi Valøyan in Trøndelag, a fish farm that is protected from the open ocean by only a few small islets and skerries. The personnel meet at the docks at 0700 and sail out to the fish farm in a 13,5m catamaran location vessel. The visit allowed for close observation of all activities at the fish farm, from daily inspection of each pen to small repairs, installing net in a pen, and delivery of fish from well-boat. Much time was spent in the break room casually talking with the crew while waiting for other support vessels to arrive and work at the fish farm. The 2-day trip with a well-boat was related to this visit at Valøyan. An opportunity arose to join Frøy's Gåsø Jarl for two days as it would return to Valøyan for another delivery later on. While following activities on the fish farm and service vessel was manageable because they usually work only during the day, it was harder to keep track of everything on the well-boat where operation is around the clock. The purpose was to observe everyday work, and get the chance to perform further, unstructured interviews of crew both at fish farm, service vessel, and well-boat. Again, building on already attained knowledge, and hopefully manage to fill some of the gaps that were revealed during model sketching, and possibly validate other parts of the understanding. Observations covered both what they were doing, and how, but also communication with other parts of the organization, change of plans, information flow and decision-making. Lots of knowledge and practices are not written down and are not easily communicated but rather need to be observed in order to understand considerations that are being made. Since the crew themselves have learned through experience it is not straight forward for them to communicate their perceptions and considerations in a terminology that is familiar to researchers. Consequently, combining observations with subsequent interviews has a significant benefit compared to independent interviews.

3.1.2 Modeling

Modeling means to represent system components and rules in a way that enables imitation of a real-world system. Knowledge about system behavior and what relations that are of interest to investigate determines the appropriate modeling approaches with respect to method, assumptions, simplifications, fidelity, and scope. All these choices are part of an iterative process where adjustments may be necessary as more is learned about the implications of modeling selections. Iteration is about trial and failure, for example in formulating rules about behavior based on collected information, and then those rules turn out to be wrong and must be reconsidered. A concrete example could be assuming all service vessels follow operational limits based on wave height, but later learning that limits also depend on wave direction or that wind speed is the most important. With modeling as an integrated part of the process of understanding the system behavior, this can in turn entail need for changes to its structure. Practical applicability of constructed models is potentially a significant limitation, considering the choice of applied research with usefulness for industry, as opposed to fundamental research. Finally, verification and validation of the model is performed to make sure that components and the combined model behaves as intended and in accordance with useful comparisons that can be made from real-world systems (Sargent, 2013).

Purpose of the model, that is what investigations it shall enable, is the basis for understanding the type of problem that needs to be solved, which in turn determines modeling approach. In this study queueing system modeling using DES, mathematical modeling, and hydrodynamical response models were chosen for different purposes; in short for mapping of causal relations for the high-level system of fleets, search for optimal relations, and causal relations for single-vessel behavior, respectively. Scope is related to project boundaries as well as what systems should be included in detail or can be represented as external inputs such as probability distributions. For instance deciding that frequency of mission requests from fish farms are represented by probability distributions rather than modeling subsystems and activities that lead to mission requests. Fidelity is another aspect related to practical applicability and project boundaries, as it is concerned with the level of detailing and thus similarity with the real-world system. Reduced fidelity does not necessarily reduce validity and is a way in which modeling can be simplified, need for data can be reduced, and solving models can be made faster. For instance, it might not be useful to put significant effort into estimating emissions of a fleet to the gram of CO_2 if the purpose is to determine which of two fleets that has lower emissions. Assumptions and simplifications are also necessary for models to be practical. Recreating the full complexity of a real-world system is not even technically possible. An example of an applied assumption is that people being tired or having different levels of competence does not affect vessel performance. An example of a simplification could be to model sailing speed only as a function of wave height and design speed. Assumptions and simplifications can be made unconsciously, due to a lack of understanding of the real system. Validation should reveal serious misconceptions or gaps, so that the reason for significant deviations can be studied and the model can be improved.

3.1.3 Investigation and use of models

Studying effect on system behavior from changes in input values, and determining causal relations requires a design of experiments that is suited to model and purpose. Design of experiments means to have a plan for what input values to test for in order to attain the results needed to establish the desired information. Efficient use of resources is often a priority in the design, however uncertainty in results can require some robustness in the design of experiments. Consider, for instance, a study which is to establish in what weather conditions a fleet of vessels no longer can perform satisfactorily, by testing performance in several predetermined metocean conditions. It is not known what weather conditions that are close to that intersection, so the design of experiments is based on an assumption of the probability that useful insight is gained from performing those experiments. Maybe the desired information is not found, or the opposite, it is achieved quicker than anticipated. When performing controlled parameter studies changes in output are causally related to changes in inputs. However if too many input variables are varied or too few tests are performed on different input variations, it is not possible to establish causal dependencies with certainty between single inputs and outputs. For example, if both weather, number of vessels, and number of fish farms in a system are changed between experiments it is difficult to determine the effect of only changing number of vessels.

Common designs of experiments for mapping of a range of input variations are simple design, full factorial, and fractional factorial (Jain, 1991). That is, when seeking to understand how changes in several inputs affect outputs, there are proposed, structured approaches for how to vary inputs in order to create an impression of the general relation. For example, how vessel speed, operational limit, and number of vessels affect the number of completed operations in a scenario, can be described by marginal and dependent functions. These functions can be determined based on experiment results. Simple design assumes independency between the input factors, while the factorial approaches assume there is dependency between the factors. In case of the previous example, dependency could mean that the effect of vessel speed on the number of completed operations depends on the operational limit. These, and other experimental designs, are often used to establish “functional” descriptions of the dependency for the complete relevant range of values. In this research project simple scenario analyses and case studies were chosen as the preferred method for analysis, due to the large number of possible dependencies and objective of indicating potential effects. For example, in Slette et al. (2022) only two weather scenarios were considered to show that weather does impact the response progress, but no attempt was made at describing a function for that relation. This choice is also motivated by the applicability of the investigation, that is, achieving high accuracy on small variations has lower value for generalization than indicative results for large effects. Again, in Slette et al. (2022) accurate descriptions for effect of weather on response progress would not be equally valid for other systems. The goal was to provide methods and indicate relations to guide interest in further investigation or application of methods in practical, concrete problems that the industry faces.

Internal validity is good because the methodology allows adjusting exactly the parameters for which the effects are studied. The problem is the validity of the model with respect to the true effects, and that only the types of effects that are modelled are registered. Validation of models based on comparison of results were limited to evaluation based on what was considered realistic, due to lack of useful datasets for direct comparison.

External validity is also good as long as the models are valid with respect to the true effects. External validity is concerned with the generalization of the results – that is, if they apply to other situations than the study itself (Leedy & Ormrod, 2015). The studies are in controlled environments and thus all inputs are known so there are no unmeasured x-factors. However, there may be real-life factors that influence the results which are not considered in the model, either because they were considered too minuscule to be of significance or because they were unknown.

Depending on modeling choices it is also possible to study the “why” to some extent. That is, for example, analyzing intermediate results in a time-domain simulation such as DES trying to interpret how the chain of effects build up and why the final result turns out the way it does. An example could be to follow the operation of a single vessel: “this fleet is better in this scenario because at time 34 we see that vessel 6 can serve fish farm 2, while for the other fleet this was not the case.” However, it can be hard to understand or see something like this in the behavior of a large system.

3.2 Evaluation of research approach

In this section, an evaluation of the research approach is presented, covering experiences from execution of the research project. What worked well and what did not go as planned?

Structuring the project with literature review and domain study before model drafts, interviews and field trips did work well for creating a wide and thorough understanding of the fish farming system in relation to vessels and vessel operations. The iterative approach of combining pure information collection with model drafts was successful, but it is possible that other, for instance, more linear approaches also could have yielded good results. It turned out that the modeling stage required more iterations than anticipated, was more tedious, and did entail significant technical challenges. The higher number of iterations was due to several reasons including practical considerations such as slow running models that had to be streamlined, improved understanding of the system required changes to models, and insufficient competence on the software tools resulted in poor technical modeling which had to be fixed when revealed at later times. The latter was especially a problem for modeling in SIMA where software limitations were revealed late in the process, meaning that insufficient knowledge of the tool led to a need for restructuring models and redirecting method development. It should also be noted that the possible challenges of constructing advanced software programs were not fully appreciated in planning. Much time was spent on building and verifying code and learning both software programs and code languages.

Being part of SFI EXPOSED meant that it was reasonable to design a methodology utilizing their expertise, access to industry, and data sources and infrastructure possessed by the center. This did, mostly go to plan. However, after getting to know the participants and learning about the collected data it became clear that there are restrictions on the time other participants can spend on providing assistance. In addition, even though access to data is granted, it can still be a challenge to retrieve it, due to technical barriers. Data quality and data format also led to significant additional efforts in order to be implemented in models. As an example, data collected for one part of the center may not be on a form that is easily applicable to other uses or may have no value unless some extra information was collected at the same time, for example, metadata on the context in which it was registered. In some cases this meant that data initially believed to be useful for this research project could not be included.

Field trips were even more valuable than expected. In addition to providing access to details and observations that are not available by other means, it also provides a platform for discussions and conversations with personnel at fish farms and vessels that makes it both easier for them to explain and for the researcher to understand because of the shared physical context. Having a certain level of knowledge about the system prior to field trips was an advantage and improved the value of the trips. In retrospect it would probably be beneficial to have more industry experience to do this research more efficiently. That is, the more one knows, the more one sees and appreciates. This is especially true for details such as differences in practices and vessel designs. However, there might also be a case made that a researcher with less experience in the industry is more open for new ideas and less restricted by current practice and unwritten rules.

A limitation of the selected approach is the difficulty of direct validation of models against real-world systems. However, with the purpose being to investigate system configurations that do not exist, it is difficult to see a method without this limitation. Validation towards simpler systems or subsystems could have been performed if useful datasets were available.

Finally, consequences of the covid-19 pandemic led to fewer field trips than initially planned due to fear of crew being infected and quarantined. In the Norwegian fish farming industry this had repercussions well into spring 2022. For a period in 2020 and 2021 the pandemic also reduced access to industry and attendance at conferences because of diverse effects from disease and lockdowns. Another unforeseen challenge was the difficulty faced by the journals when searching for relevant competence to review the research papers for publication. Papers were sent to industry journals with the purpose of improving availability of the research to the intended audience of practitioners. However, these journals can find it difficult to gather appropriate competence on subjects like vessel design and maritime logistics, rather, they often have primary focus on biology, fish health, and production systems. A result was that one paper submitted in 2020 was in review for 17 months. These consequences were unfortunate and unexpected, but there was no quick solution for how to get less affected by the pandemic.

4 Results

At the beginning of the research project a research question was formulated, and three related research objectives were defined. Achieving those objectives will contribute towards gaining insight on the research question. In this chapter, the results of the project are presented and contributions towards research objectives are explored in detail. This covers research papers, fulfillment of research objectives and contributions of the research study to the literature. First, the research papers are presented, including abstracts, relevance to the thesis, declaration of authorship, and information on where they are published. Next, the research objectives are discussed with a description of how the papers have contributed to their fulfillment. Finally, the contributions of the research project are presented, including the motivation behind the contributions and their relations to research papers and research objectives. The research project resulted in five research papers, of which I was the main author in four, and co-author in one. All papers are either published or submitted to peer-reviewed international journals. The papers were largely written in parallel, and only two papers had a direct dependency; paper 4 extends on the method developed in paper 2. Relations between research objectives, research papers, contributions are illustrated in Figure 41, with the structure being that research objectives were derived from the research question, papers being based on research objectives, and thereafter leading to contributions.

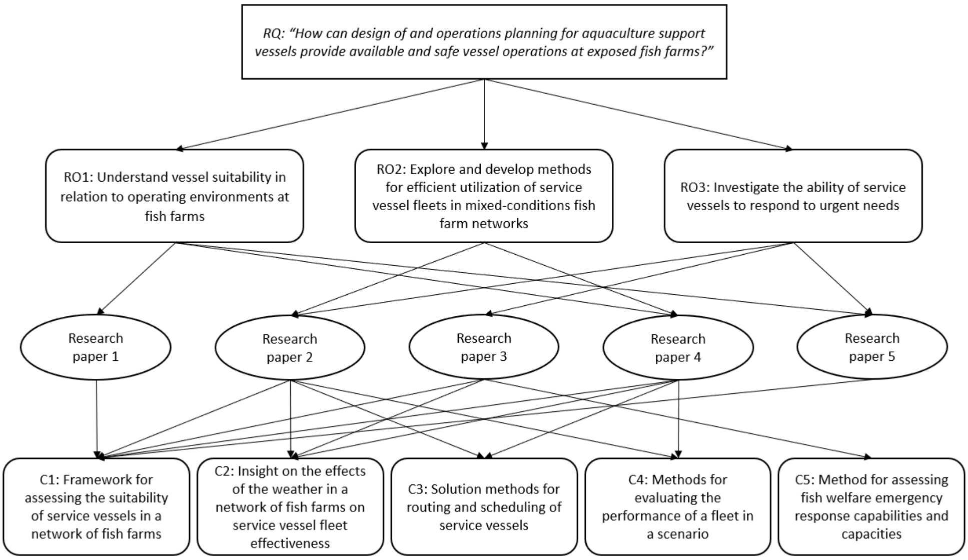

Figure 41. Relations between research objectives, papers, and contributions in the research project. The figure is inspired by Pettersen (2018).

While paper 1 and 3 are related to only one research objective, paper 2, 4, and 5 are related to two each. Further, paper 2, 3, and 4 are related to the most contributions. All papers are related to contribution 1. Focused versions of the figure are revisited in Section 4.2 and Section 4.3 covering fulfilment of research objectives and presentation of contributions.

4.1 Research papers

4.1.1 Paper 1: Emission abatement

Cost-emission relations for maritime logistics support in aquaculture
Slette, H.T.; Asbjørnslett, B.E.; Fagerholt, K.
Journal of Physics: Conference Series, Vol. 1357, 2019

Abstract:
This paper presents a method for evaluation of the economic cost of reducing the emissions from a fleet operating in the aquaculture industry. The method accounts for the fact that different fleet compositions perform differently in a given operating environment. A simulation model tests the fleets, returning the achieved mission coverage, total operating cost and emissions. The cost and emissions for each fleet are adjusted for coverage before their relations are analyzed using regression on the Pareto frontier. A case study is performed, estimating the cost of 5%, 10%, 20%, 50% and 100% reductions in CO2-emissions from well boat operations.

Relevance to the thesis:
This paper covered the first finished model for evaluating fleet performance, with a DES model for simulating system behavior and post-processing of the output to adjust the performance measures, that is, costs and emissions, to consider mission coverage. The model and method were presented at a conference, which entailed valuable feedback for further model development. Assessing emission reduction measures in relation to performance is necessary for reliable estimates on cost and effect. Further, due to the collaborative manner in which vessels serve fish farms, that it is normal that a fleet of vessels share the workload, the accuracy of the assessment is improved when considering the fleet level. However, it is clear that a more realistic routing strategy must be implemented to increase validity of the model.

An added value of this research paper was an indication of the benefit that can be derived from these types of models compared to direct analysis of input data, for example, in terms of data sheet of emissions per kWh for different fuels. For complex systems it can be difficult to understand or predict the full interaction between components and therefore also the final result. Hence, the model was found to provide a benefit.

Declaration of authorship:
Hans Tobias Slette: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Bjørn Egil Asbjørnslett**: Conceptualization, Writing – review & editing, Supervision. **Kjetil Fagerholt**: Conceptualization, Writing – review, Validation.

4.1.2 Paper 2: Aquaculture service vessel routing

The Aquaculture Service Vessel Routing Problem with Time Dependent Travel Times and Synchronization Constraints
Lianes, I.M.; Noreng, M.T.; Fagerholt, K.; Slette, H.T.; Meisel, F.
Computers & Operations Research, 134 (2021) 105316

Abstract:
This paper studies the Aquaculture Service Vessel Routing Problem (ASVRP), which is an important planning problem arising in sea-based fish farming. In the ASVRP, there is a set of fish farms located in the sea, where each fish farm has one or more service tasks to be performed by a given heterogeneous fleet of service vessels with different capabilities. Some service tasks require simultaneous operation of more than one vessel and might also have time windows and precedence requirements. Furthermore, varying weather conditions make the sailing times and the service times of the tasks time dependent. The objective of the ASVRP is to maximize the value of the service tasks performed within a given planning horizon. We propose a time discrete optimization model for the ASVRP, formulated as a time dependent, prize collecting vehicle routing problem with synchronization constraints and time windows. Furthermore, we present an Adaptive Large Neighborhood Search (ALNS) heuristic for solving the problem. Results on a number of test instances based on real world data show that both the ALNS heuristic and a commercial solver are able to find high quality solutions for small problem instances, while the ALNS heuristic is superior when the problem size increases.

Relevance to the thesis:
The paper presents a model for optimal routing of heterogenous fleets of vessels and diverse demands both with respect to when and how they can be executed. This was both found to be a research gap in the literature and thereby useful in itself, while also a necessity for estimation of behavior and performance of fleets in further models. A formal mathematical problem formulation is presented and an ALNS solution heuristic is tested for realistic routing problems covering sets of aquaculture support vessels with diverse characteristics. Working on the problem formulation improved insight into the problem and the method proved capable of solving realistically sized problems so that it could be applied in further studies.

Declaration of authorship:
The paper is based on the master's thesis of Ingeborg Margrete Lianes and Maren Theisen Noreng (Lianes & Noreng, 2020). Kjetil Fagerholt was their main supervisor and Hans Tobias Slette co-supervised the master's thesis. In writing of the paper, Hans Tobias Slette was a co-writer. He held the domain knowledge and practical understanding of the problem and helped relating it to the operations research competence of Kjetil Fagerholt, Ingeborg Margrete Lianes, Maren Theisen Noreng, and Frank Meisel. He also had a major role in the revision process.

4.1.3 Paper 3: Fish-welfare emergency response

Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming
Slette, H.T.; Asbjørnslett, B.E.; Pettersen, S.S.; Erikstad, S.O.
Aquacultural Engineering, Vol.97, 2022

Abstract:
This paper presents a simulation model for analyzing emergency response for fish welfare emergencies in sea-based fish farming. The model enables decision-makers to evaluate the emergency preparedness level against incidents harming fish welfare and the benefit of additional measures such as dedicated emergency response vessels. The proposed model simulates how the vessel operations of a sea-based fish farming system develops over time and tests the emergency preparedness at regular intervals by simulating the emergency responses. The progress of each emergency response is logged and is used to establish first response time, response progression, and response completion duration. A case study is performed assessing the emergency preparedness of two sea-based fish farming systems, and the effects of adding a dedicated emergency response vessel. The results indicate that the value of a dedicated emergency response vessel is more prominent for smaller systems.

Relevance to the thesis:
This paper shows a different approach to fleet performance than paper 1, and this required a new model to allow description of the relevant behavior and output of results. Emergency preparedness and response is not considered in any other papers of the research project and constitutes an important research area with respect to the research question.

The paper investigates emergency preparedness and response for systems where vessels used in response are occupied with regular operation most of the time, in contrast to offshore O&G where there are dedicated ERRVs. This means that resources are not located at fixed positions for optimal response coverage and that they may need to recommission in order to be able to respond to the particular emergency. Studying the effect of preoccupation on availability for sudden change of plans is only done in this paper. Other models cover, for instance, rerouting with consideration of current plans and seek to minimize change due to possible entailing inefficiencies. Finally, it provides a method for evaluating and attaining insight on the actual preparedness of each fish farm when response resources are shared with others. In these cases some fish farms must wait longer before their response is initiated. The method enables analysis of response times and response progression, quantifying estimates on the real preparedness for fish farms.

Declaration of authorship:
Hans Tobias Slette: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Bjørn Egil Asbjørnslett**: Conceptualization, Writing – review & editing, Supervision. **Sigurd Solheim Pettersen**: Writing – review & editing. **Stein Ove Erikstad**: Conceptualization, Software, Validation.

4.1.4 Paper 4: Service vessel fleet utilization

Effective utilization of service vessels in fish farming: Fleet design considering the characteristics of the locations
Slette, H.T.; Asbjørnslett, B.E.; Fagerholt, K.; Lianes, I.M.; Noreng, M.T.
Aquaculture International, 2022

Abstract:
Effective utilization of service vessels in sea-based fish farming requires that the vessels are suited to the operating environments at the fish farms. This paper presents a methodology for assessing service vessel fleet performance when serving a network of farms with different metocean conditions. Fleet performance is defined as the ability to perform operations requested by the fish farms, in due time. An optimization for simulation approach is employed, implementing a routing and scheduling heuristic developed for aquaculture service vessels. A case study was performed assessing the performance of two different fleets serving a set of 21 fish farms. The variation in local metocean conditions between the farms, and how weather changes in time, challenge the operability of the aquaculture infrastructure and the effective routing and scheduling of the vessels. Hence, the results show that proper fleet composition in this context improves fleet performance. Fleet performance is substantially higher when fleet composition, routing and scheduling is based on the specific weather conditions.

Relevance to the thesis:
The relevance of this research paper to the research project is primarily related to research objective 1 and understanding effects of metocean conditions on fleet performance. This focus on investigating specific variations in weather is not present in any other parts of the project. That is, changes in wave heights, duration of sea-states,

correlation between the locations. Building on the routing heuristic of paper 2, this is also a test of how the ALNS can be implemented in practical use cases over longer periods with a rolling horizon where new information is revealed continuously, and plans must be adapted to the new reality according to priority. The method in paper 4 can be used to analyze a variety of correlations between variables, of which the case study in the paper covers only a few examples. The results provide valuable insight on some of the main topics of the thesis in terms of how metocean conditions with increased exposure relate to the performance of support vessels.

Declaration of authorship:
Conception and design were mainly the works of Hans Tobias Slette and Bjørn Egil Asbjørnslett. Material preparation, data collection and analysis were performed by Hans Tobias Slette, Bjørn Egil Asbjørnslett and Kjetil Fagerholt. The first draft of the manuscript was written by Hans Tobias Slette, and Bjørn Egil Asbjørnslett and Kjetil Fagerholt commented on previous versions of the manuscript. Ingeborg Margrete Lianes, Maren Theisen Noreng and Hans Tobias Slette have developed new software used in the paper. All authors read and approved the final manuscript.

4.1.5 Paper 5: Vessel operability and metocean conditions

Susceptibility to weather induced delays in vessel operations at marine fish farms
Slette, H.T.; Lader, P.F.; Asbjørnslett, B.E.
Has been submitted to scientific journal

Abstract:
Vessel operations performed by aquaculture support vessels at marine fish farms for Atlantic salmon are weather restricted, meaning that they should only be performed if the weather conditions are acceptable. This paper presents a method for estimating the susceptibility of aquaculture support vessels to weather induced delays when serving fish farms. A susceptibility metric is calculated based on weather statistics for fish farm locations, operational limits, and relative importance and frequency of service operations. The latter is used to determine weighting of an operation and is calculated for each season of the year. Comparing operational limits to occurring weather states and their corresponding probabilities of occurrence gives the fraction of time various operations can be performed. Susceptibility is then calculated by adjusting for their weights. A case study demonstrates the method and compares susceptibility of two aquaculture support vessels when serving a fish farm. The results show that one vessel is better suited to the weather conditions, however it is left to the decision-maker to determine significance of the difference in suitability. That is, applied assumptions and simplifications determine the accuracy of the results in terms of absolute susceptibility.

Relevance to the thesis:
This paper presents a framework for evaluating the suitability for vessel operations at fish farms, by quantifying the susceptibility to weather induced delays. The method can be used in early design for differentiating expected vessel performance and estimate suitability based on metocean data and operation profiles. To the authors' knowledge suitability of fish farm locations for service vessel operations has not been studied previously. Suitability for vessel operations is studied in other maritime contexts, but the variation in vessel designs in terms of sea-keeping abilities and operational functionality, and variations in operating environments at the locations and interface between vessel and structures requires an adapted approach. The results of the case study are not very useful, as the case study only demonstrates how the model works. The paper includes a step-by-step presentation of the evaluation of two vessels serving an exposed fish farm location. Relevance to the research project is also found in that it presents an alternative approach to modeling fleet performance compared to DES or mathematical modeling, that is, an algorithm for calculating estimates without considering operational decisions such as routing.

Declaration of authorship:
Hans Tobias Slette: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Pål Furset Lader:** Writing – review & editing, Supervision, Validation. **Bjørn Egil Asbjørnslett**: Writing – review & editing, Supervision.

4.2 Research objectives

This section describes how and to what degree the research objectives have been reached in this research project. A figure is included for each research objective describing its relation to papers and contributions.

4.2.1 Research objective 1: Vessel suitability

RO 1: Understand vessel suitability in relation to operating environments at fish farms

Paper 4 and paper 5 are directly related to this research objective. The purpose of both papers was to quantify suitability of a fleet in a context of fish farms and metocean conditions. Methods and models were established enabling broad investigations of effects of operating conditions, and further analyses on these relations are needed to fully accomplish the research objective. As mentioned in Chapter 2 operating environment can include fleet composition, operational profiles, and market conditions in addition to metocean conditions. The study of paper 4 was mainly isolated to a few variations in metocean conditions that were assumed to give insight on effect of weather for a fleet of vessels serving a set of fish farms. At the same time, differences in fleet composition were briefly investigated. Paper 4 did provide good results in the sense that clear correlations were identified, and a method was established to perform further investigations on similar systems for other correlations. Paper 5 on susceptibility to weather induced delays presents a method intended exactly for differentiating vessels and locations based on suitability in operating environments in terms of both metocean conditions and operational profiles. The case study does not yield any generally applicable results, but the method does allow for investigation of specific problems or mappings to establish relevant knowledge on the relation between suitability and operating environment.

Paper 1 on cost-emission relations is also relevant to this research objective with the broader interpretation of operating environment because it investigates suitability of variations in vessel designs in terms of different emission control measures. That is, how market conditions such as operation costs and characteristics of demands from fish farms determine suitability, that is, what the preferred emission control measures are when considering cost and estimated emission reductions.

Figure 42 shows that research objective 1 is related to research papers 1, 4, 5 and in turn to contributions 1, 2, 3, 4.

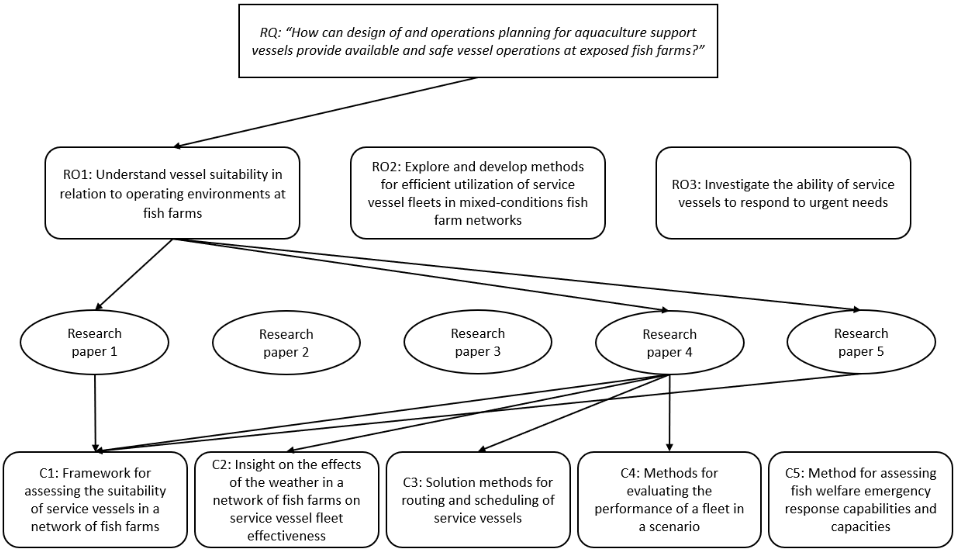

Figure 42. Research objective 1 is related to research papers 1, 4, 5 and in turn to contributions 1, 2, 3, 4. The figure is inspired by Pettersen (2018).

4.2.2 Research objective 2: Efficient fleet utilization

RO 2: Explore and develop methods for efficient utilization of service vessel fleets in mixed-conditions fish farm networks

Mixed-conditions points to metocean conditions varying between fish farms, so that availability at one fish farm does not necessarily mean that other fish farms are available at the same time. For instance, metocean conditions developing independently between fish farms. Research paper 2 presents a mathematical model and solution methods directly related to this research objective. Optimal, or close to optimal, solutions are found for routing and scheduling problems considering a fleet of vessels and a mixed-conditions fish farm network, in terms of metocean conditions, with individual forecasts for each fish farm. An exact solver is used to solve small problem instances, with up to 40 fish farms, while an ALNS heuristic is superior for larger problem instances. Optimality is related to a profit function, where completed operations give profits and use of vessels incur costs. Hence, efficient utilization is covered to the extent it can be represented by operational costs and profits from completion of operations. Further exploration of relevant methods is done in the literature review in Chapter 2 and the review in paper 2. However, the finding was that there were no suitable methods in the literature for solving the complete aquaculture service vessel routing problem, showing the need for paper 2.

The ALNS heuristic of research paper 2 was extended in paper 4 to be integrated in a rolling horizon simulation for long-term re-routing of the vessels. Here, vessels were routed over 100-day periods, making 5-day plans every 3rd day considering updated information on weather forecasts, demands from fish farms, and what operations are finished. Other routing and scheduling methods can be integrated into that framework, enabling exploration of their performance for a rolling horizon application.

Figure 43 shows that research objective 2 is related to research papers 2 and 4, and in turn to contributions 1, 2, 3, and 4.

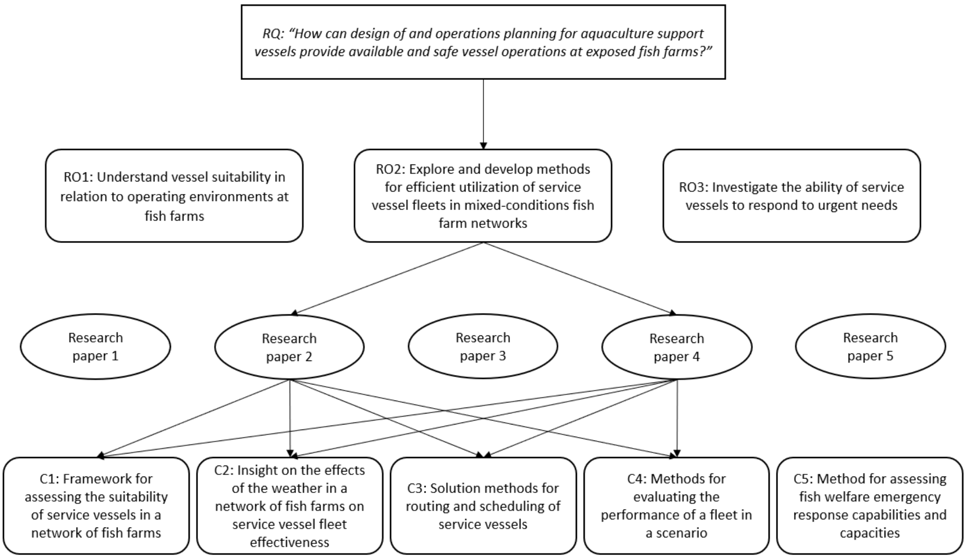

Figure 43. Research objective 2 is related to research papers 2 and 4, and in turn to contributions 1, 2, 3, and 4. The figure is inspired by Pettersen (2018).

4.2.3 Research objective 3: Response to urgent needs

RO 3: Investigate the ability of service vessels to respond to urgent needs

Urgent is here understood as both suddenly arising and requiring immediate resolution. Paper 3 presents a model and a case study on the response capability of a fleet of vessels, with and without dedicated ER vessel. The model enables estimating consequences of emergencies as a result of response measures, and thereby quantifying the ability to respond. That is, ability to respond is given as the number of fish lost, a graph showing when fish are moved, or how long it takes before first response is at the scene. Two main questions related to the research objective are match of vessel capabilities towards requested response types and scale, and availability of vessels in terms of how quick they can initiate response. The method in paper 3 covers mobilization of resources and necessary preparations to be made to go from one mission type to another. The method presented in paper 3 allows for detailed inspection of various system configurations and emergency scenarios. In addition, the case study is intended to be close to realistic, and as such the results can be indicative for emergency response capability of similar systems and emergencies.

Paper 5 on susceptibility for weather induced delays is also relevant here because it presents a method for establishing expectations on how often vessels are able to perform various operations throughout different seasons, with respect to metocean conditions. There are operational limits even for emergency response, thus the method could give indications on availability of different locations for response to urgent needs such as emergency response.

If decision makers determine that the urgent need is not engaging a full mobilization of all resources, ability to respond is a question of trade-offs against other considerations. For instance, taking a well-boat out of normal operation induces a cost. In such cases, the method from paper 2 can be used to find optimal routing of resources, maximizing positive effects of response while minimizing negative effects of taking resources out of normal operation. Solving this routing problem for different scenarios can help map ability to respond.

Figure 44 shows that research objective 3 is related to research papers 2, 3, and 5, and in turn to all contributions.

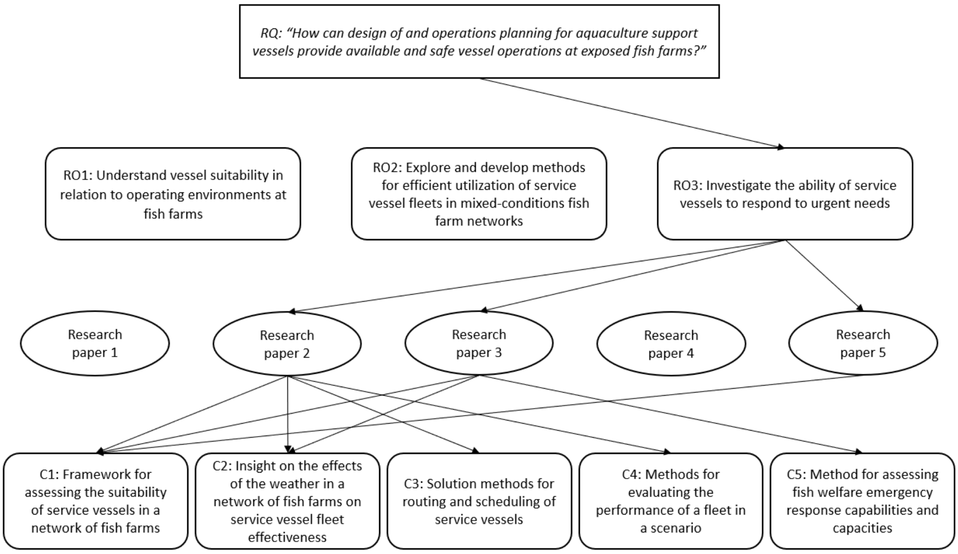

Figure 44. Research objective 3 is related to research papers 2, 3, and 5, and in turn to all contributions. The figure is inspired by Pettersen (2018).

4.3 Contributions

Here contributions of the research project to the literature are presented. Each contribution is stated, and the motivation behind them is given in addition to in what way this research project has supported the contributions.

4.3.1 Contribution 1: Suitability of service vessels

C1: Framework for assessing the suitability of service vessels in a network of fish farms

Helps understand what vessels are the best to serve a set of fish farms considering metocean conditions, operation demands, interface between vessel and structures, and stakeholder interests.

Why: Determining how differences in vessel designs or fleet composition affect various measures of performance related to vessel operations can give improved utilization of vessels, lower costs, and improved operation of fish farms. No methods with sufficient adaption to the aquaculture industry were found in the literature.

How: This contribution is made by all papers of the research project. Paper 1 shows how vessel fleets with different emission reduction measures can be compared with respect to an overarching objective where mission completion is balanced with cost and emissions, constituting suitability. Paper 2 and 3 both present methods for evaluating how well a fleet can fulfill short-term obligations which can be considered a measure of suitability. That is, how suited the fleet is to meet normal service needs and emergency response needs, respectively. Methods in paper 4 and paper 5 enable assessments covering longer periods. The method in paper 4 extends the method of paper 2, greatly increasing the period in consideration. Paper 5 proposes a method for assesses the susceptibility of weather induced delays for one or more vessels serving one or more fish farms given their historical weather. Figure 45 shows that all research papers are related to contribution 1.

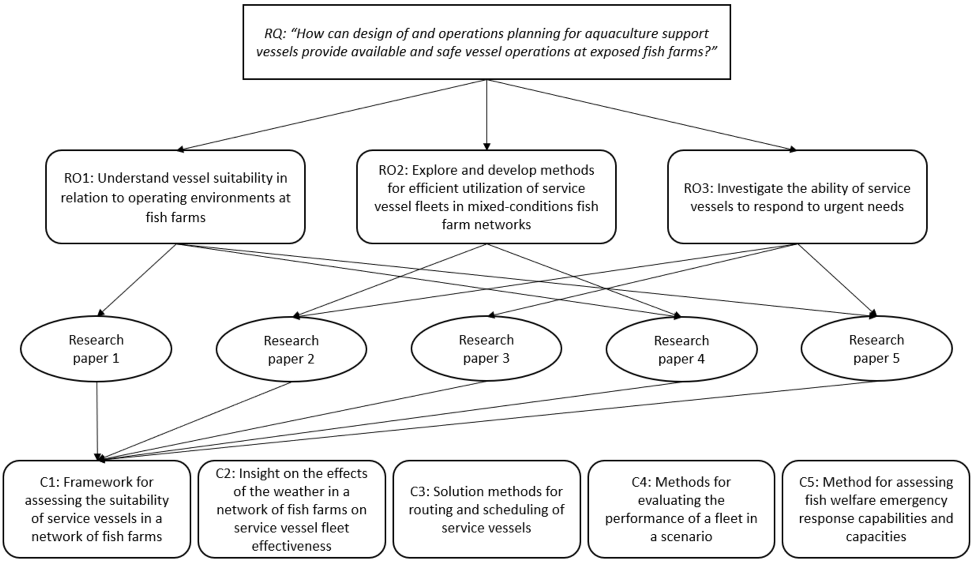

Figure 45. All research papers are related to contribution 1. The figure is inspired by Pettersen (2018).

4.3.2 Contribution 2: Weather impact on fleet

C2: Insight on effects of weather in a network of fish farms on service vessel fleet efficiency

Enables well-informed planning of geographical placement of fish farms with respect to the effects that this may have on operational availability of the fish farms. Useful when fish farmers expand their operations to include more exposed fish farms.

Why: Expansion into more exposed areas necessitates more knowledge about how weather affects operational accessibility and hence vessel fleet efficiency. Framework for assessment as mentioned in Contribution 1 is useful, but general understanding of effects which can provide insight in decision-processes without the need to perform such assessments is also valuable. Connecting experience with results from case study assessments can enable decision makers to gain insight on specific metocean conditions of contemporary problems, also in situations where the need and justification of thorough assessments are not present. That is, for instance, initial calculations in early design.

How: Case studies presented in papers 2, 3, and 4 provide insight on how differences in weather affect vessel fleet efficiency. In paper 2, fleet performance was tested for 20, 40, and 60 fish farm instances with weather scenarios: perfect, September, and January. Perfect means that weather effects can be ignored, September represents typical summer weather, and January represents winter weather, with winter having significantly rougher metocean conditions than summer. Paper 3 gives insight on how metocean conditions affect response capability, as otherwise identical scenarios are simulated with and without a wave height time series and a simple description of how wave height affects sailing time and operation. Finally, the case study in paper 4 is specifically designed for this contribution. In addition to increasing or reducing wave height time-series, variations in how height develops in time, and correlation in weather between fish farms is considered. Figure 46 shows that research papers 2, 3, and 4 are related to contribution 2.

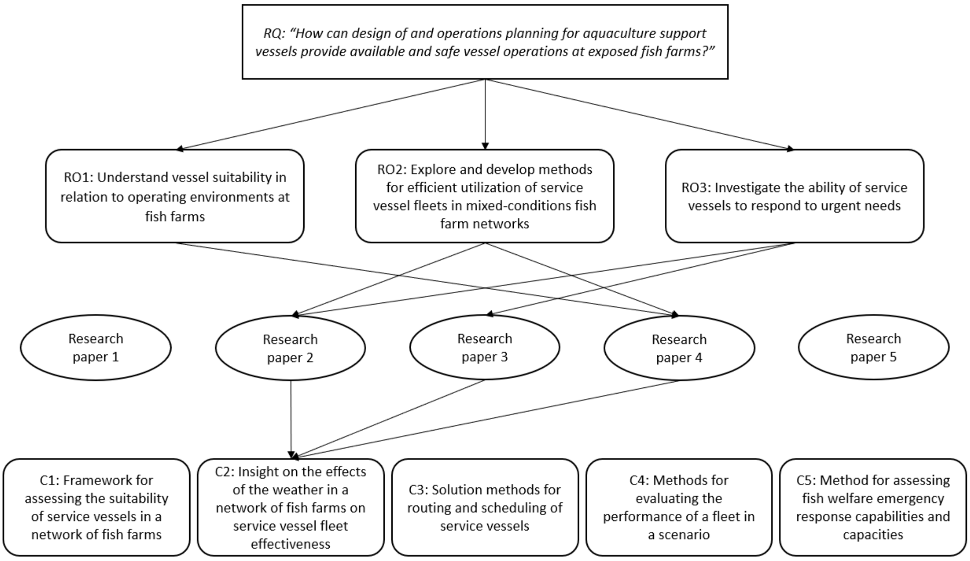

Figure 46. Research papers 2, 3, and 4 are related to contribution 2. The figure is inspired by Pettersen (2018).

4.3.3 Contribution 3: Routing and scheduling in fish farming

C3: Solution methods for routing and scheduling of service vessels

Opening for optimal utilization of vessels, improving mission capacity, cost, emissions, and safety compared to routing strategies used in the industry today.

Why: Routing and scheduling of vessels is not a new concept, however, as highlighted in the literature review in chapter 2, no useful methods exist for aquaculture service vessels. Currently, vessels are often routed individually and by use of an excel sheet, human intuition, and manual calculations. Routing is an important part of the efficiency of a fleet of vessels and realizing the potential of the fleet can be a complex combinatorial problem requiring a dedicated solution method. Overlap in functionality and capabilities between vessels opens for a great potential for synergetic effects if they are considered as a fleet. Further, accurate and fair assessments of fleet compositions in decision-making is enhanced by an objective routing and scheduling method. That is, today fish farmers use different strategies when routing vessels and these may favor some types of fleet configurations over others. For instance, they can be closer to the optimal solution for a fleet where no vessels have overlapping functionalities compared to a fleet where most vessels have shared capabilities, simply because the former is an easier problem to solve.

How: Paper 2 presents routing and scheduling methods for solving the aquaculture service vessel routing problem, which covers all relevant main aspects found in aquaculture. The methods were tested for various problem instances covering from 20 to 124 fish farms, 14 task types, and 6 vessel types with different task compatibilities. Even for the biggest problem instances solutions within 2% of optimality were found in less than one hour using the ALNS heuristic. As paper 2 is concerned with solving the static problem, the method was extended and integrated into a rolling horizon framework in paper 4 to cover the dynamic problem. That is, where operations are completed, new operations are requested and new information about weather forecasts is revealed, necessitating re-routing of the vessels at regular intervals. Solution quality for the method in paper 4 was not evaluated, however as it is based on the mentioned ALNS heuristic it is expected to be good. Figure 47 shows that research papers 2 and 4 are related to contribution 3.

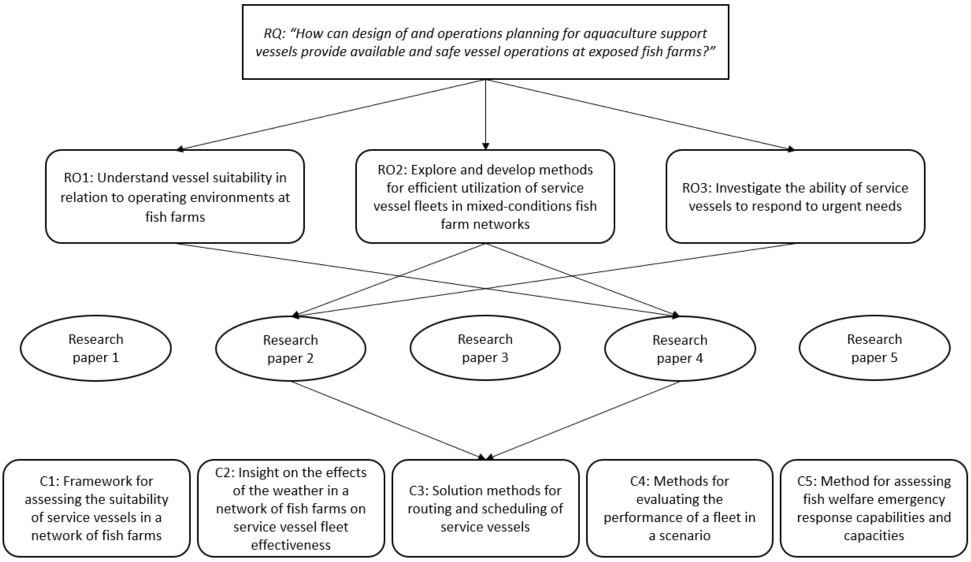

Figure 47. Research papers 2 and 4 are related to contribution 3. The figure is inspired by Pettersen (2018).

4.3.4 Contribution 4: Evaluating fleet performance

C4: Methods for evaluating the performance of a fleet in a scenario

Analyzing vessel operations at fish farms over periods in the order of 100 days for scenarios describing weather and market conditions and demands for operations. For instance a warm summer with high lice pressure requiring more delousing operations.

Why: Descriptive measures such as operational limits, engine power, and number of vessels are not of interest as such, the interest lies in the derived performance measures such as costs, emissions, or number of completed operations. In addition, it is often relevant to estimate performance for a scenario rather than some general expression, for instance an average over time. Scenarios can be useful to establish estimates on what-if or worst-case analyses, or study a concrete situation to provide decision support. For instance, if an unexpected situation arises and the decision maker considers spot charter of an extra vessel to meet all mission requests. Scenarios can include variations in weather, market, operation requests, or specifics of fish farms such as their relative positions or fish farm concept type.

How: The methods presented in paper 2 can be used for this, simply by solving the routing and scheduling problem for the desired scenario specification, and registering the value of the objective function as the performance. This presupposes that the full characterization of the scenario can be described in terms of the input parameters used in the model, and that the desired performance measure can be translated to profits and costs of operation. The former relates to the fact that the model has a set number of input parameters, and if a scenario must be described using other parameters, this can pose a challenge. Profits and costs do not have to be given in terms of monetary units, however since the performance is given as a single value, both positive and negative effects that are to be considered must be translated to a shared unit to determine contribution to the solution performance. While paper 2 allows for evaluating scenarios lasting for up to about five days, paper 4 applies a modified version of the method, using a rolling horizon framework, allowing for evaluation of longer scenarios. The case study of paper 4 covers 100-day scenarios, but any duration can be investigated, with a linear increase in computational time. Figure 48 shows that research papers 2 and 4 are related to contribution 4.

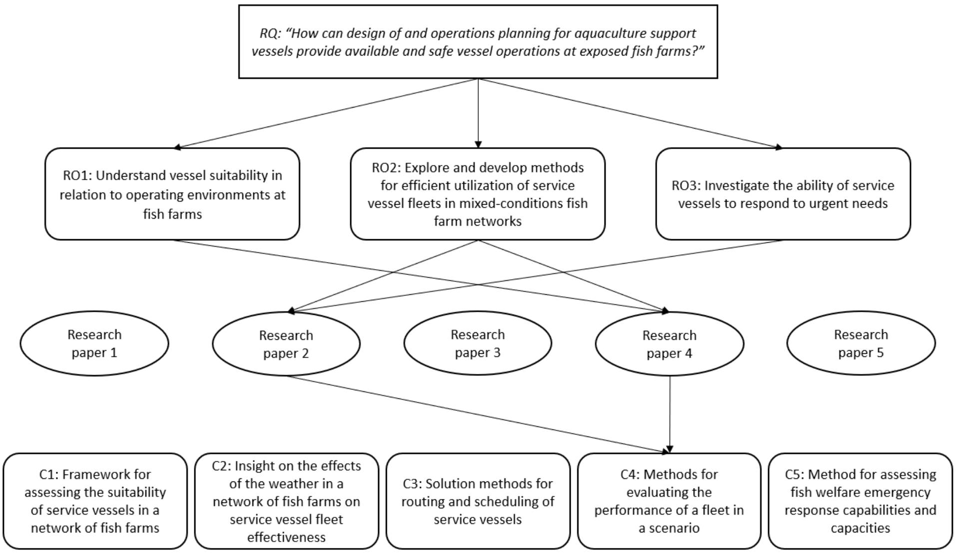

Figure 48. Research papers 2 and 4 are related to contribution 4. The figure is inspired by Pettersen (2018).

4.3.5 Contribution 5: Emergency response capabilities

C5: Method for assessing fish welfare emergency response capabilities and capacities

Allows for considering outcomes of emergencies in decision-making processes for determining preparedness. That is, when determining preparedness resources and strategies, related estimates on consequences of various emergency scenarios can be used as decision support. In addition, bottlenecks and shortcomings of response strategies and resources can be identified and acted on.

Why: Fish welfare emergencies should not be taken easily – fish is not simply biomass but living creatures with intrinsic value beyond what humans attribute to it. Having emergency preparedness capacities that are able to exercise an acceptable response is therefore important. In addition to reducing unnecessary suffering for the fish, there are also economic and social benefits for fish farmers related to good emergency preparedness and response. Achieving this requires methods for estimating quality of preparedness. No useful methods were found in the literature.

How: The method presented in paper 3 allows for testing of emergency preparedness in terms of resources and strategy. Time until first responder arrives, progression of the response, and time until response is complete are given as performance metrics. Relevant mortality rates or other functions describing fish welfare can be combined with the metrics to give numbers for consequences of the emergency and response. For instance, how many fish that are likely to die in case of a HAB with a given emergency preparedness. The method covers mobilization of vessels that are busy performing other operations and thus must complete necessary preparations before responding, as well as dedicated resources that can be placed on stand-by at desired positions. Further, it considers effects of weather on sailing times and operation. Figure 49 shows that research paper 3 is related to contribution 5.

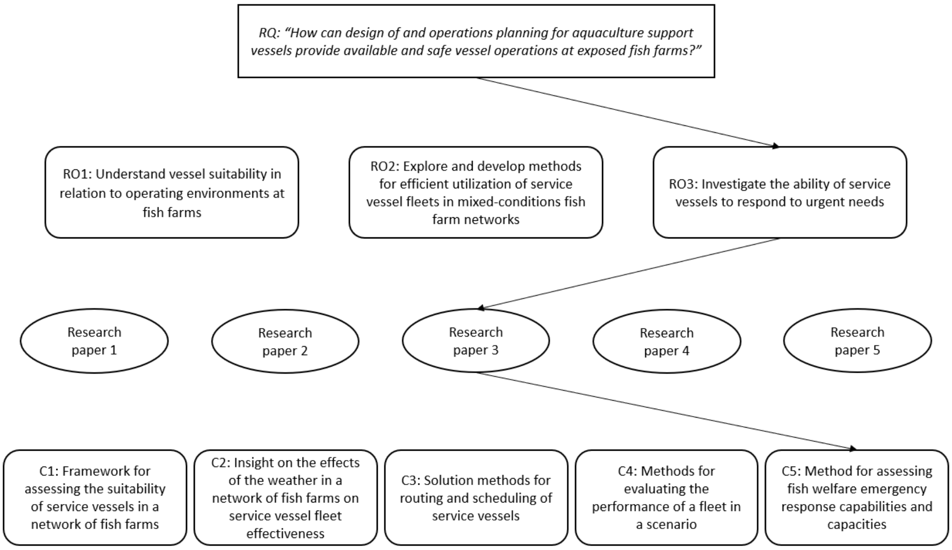

Figure 49. Research paper 3 is related to contribution 5. The figure is inspired by Pettersen (2018).

5 Discussion

In this chapter, two main topics are discussed: validity and impact of the results. Validity covers to what degree results can be used to provide insight on problems that are of interest to the industry. Traceability, transparency, and appropriate use of methods are key aspects in advocating usefulness of results. Impact of results are explored in relation to current industry practices, future research in academia, the role of authorities, and growth of exposed aquaculture. Finally, a discussion is given on how the covid-19 pandemic affected the research project.

5.1 Validity of results

Validity relates to the truthfulness of, for instance, a model, approach, result, or statement. This section covers discussions on several aspects of the research project, which in total support the validity of the results. First, the validity of the research question is covered, then the quality of my understanding of the industry and context with respect to performing relevant investigations. Finally, validity of applied methods is discussed.

Expansion of the fish farming industry into more exposed areas entails increasing susceptibility to weather. Rougher metocean conditions demand new approaches to design and planning of vessel operations both for everyday operations and emergency preparedness. SFI EXPOSED was initiated by the industry as a result of wide recognition of the need for research and development to achieve satisfactory solutions for vessel operations at the most exposed locations. Safety, fish welfare, emissions, environmental effects, and costs must all be considered and managed in an exposed environment. The nature of marine operations and handling of fish entails weather restrictions in terms of operational limits, and, in turn, a need for solutions on how to improve operations while complying with these constraints. Understanding restrictions and opportunities for each vessel and cooperation between vessels in the operational environment is crucial to succeed. The research question therefore represents a precise and concise interpretation of the core challenge related to vessels and vessel operations at exposed fish farms.

Close contact with industry and researchers, especially through SFI EXPOSED, over a period of four years has led to a comprehensive understanding of a wide range of aspects of the industry. This includes dialogue with service vessel companies, fish farmers, technology providers, and service providers, in addition to researchers at NTNU, SINTEF Ocean, and Institute of Marine Research. Even though I am still learning something new every day, I am confident that main concepts of design, operation, and considerations in decision-making processes are sufficiently well understood for fish farming, so that proposed methods, models, and insight can contribute to advancing the industry. Much of the insight is supported by several field trips visiting vessels and fish farms, with full access to talk with crew, observation of operation, and studying technical designs and solutions.

The problem covered by the research question is wide and can be divided into several layers of complexity. Insight is attained by investigating each layer and understanding relations between them. It is like peeling an onion, see Figure 50.

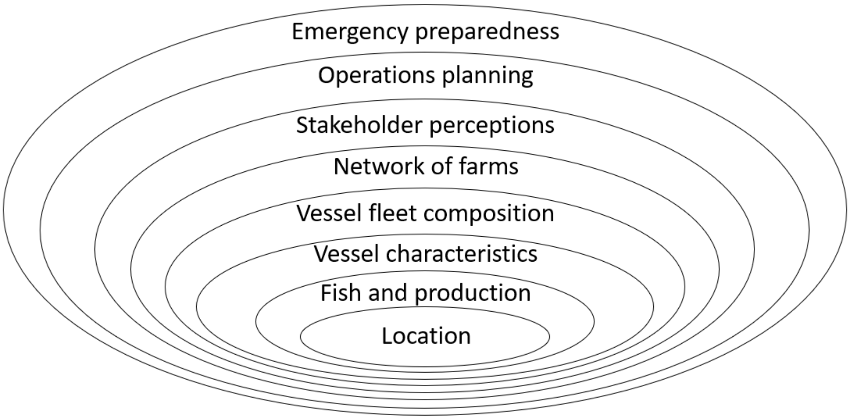

Figure 50. The problem covered by the research question can be illustrated as an onion with several layers. Valid solutions require understanding of each element and how their combination affects total system behavior.

Starting from the core with the most basic premises, characteristics of fish farm locations, fish welfare and production cycle set the fundamental frame for decision making for vessel operations. Location characteristics cover, for instance, metocean conditions and how these can be represented and understood in a way that is useful for decision-making with respect to vessel operations. Similarly, it is necessary to know what aspects about fish welfare and production that impose limitations on the solution space for operations. Next, understanding of how vessel design affects its seakeeping abilities, what operations it can perform and its compatibility with individual fish farms opens for attributing usefulness to vessels relative to the purpose of serving fish farms. Since more than one vessels serves each fish farm, vessels must be seen in context of a fleet, allowing for cooperation between them and elevating evaluation of usefulness to the fleet level. Going from considering one fish farm to a network of fish farms, aspects such as relative positions, variations in metocean conditions, correlation in operating environment, and various constraints and regulations impact vessel fleet operation. Examples of conditions describing operating environment include mission requests, fish sizes, disease, sea lice, and farm layout and design. So far, objective physical reality has been used to describe the system and interactions, however, the human factor influences actual behavior, and this is colored by stakeholder perception. This covers, for instance, both inaccurate observation of the world and subjective opinions on probabilities. This is amplified by roles and disparities in available information. For instance, a sailor and a manager do not have the same goals or impressions. Managers seek to maximize income and minimize costs, which includes efforts to charter vessels to customers and plan operations. Planning requires incorporating all aspects previously mentioned as restrictions and inputs to a procedure for determining what vessels to direct to various operations, and when. Planning problems vary depending in the duration of the considered period and the type of decisions to be made. Longer horizon often entails higher costs and more uncertainty. For example, deciding on procurement of a new vessel with an expected 10-year return on investment versus what vessel to send to a particular operation demand next Monday. So far, only normal operation is covered, however emergencies do arise, and preparedness and response must be considered within the context of all previously mentioned aspects.

Following validation of the problem and understanding of relevant industry aspects, it is in place with a discussion on the applied methods in studying the problem.

Models for representing metocean conditions, including hindcast and forecast, as presented in Section 2.1 in the literature review are well validated in respective papers and associated literature. However, as most of the applications presented in that research covers open ocean metocean conditions, for instance collected data and wave spectra models, relevance for specific applications in the coastal zone depends on similarity in metocean conditions. No attempt is made to quantify deviations from this effect in this thesis. As it mostly relates to the maturity of the waves and their directionality it is not believed to drastically affect the validity of the results of this research project. In large part because the results either are methods for which this factor easily can be adjusted if necessary, or as is the case in paper 4, the results are based on variations in metocean conditions where the exact time series are presented.

Analysis of vessel responses both for free floating vessels and with connections to fish farm structures are performed in SIMA, a software program that is developed and validated by SINTEF Ocean for several applications including aquaculture (Hermundstad, 2022; SINTEF Ocean, 2022). Use of operational limits in this research project introduces a discretionary assessment as the results are affected by applied limits, even though there are no general shared limits in the industry today. Some companies have limits for certain fish farms, operations or metocean variables. The discrepancy between the setup of the methods and real conditions does reduce validity as such. Methods based on existence of clear operational limits are not valid if there are no such limits. An actor implementing the methods will have to establish necessary limits, and even though this is not the status quo, the trend in the industry seems to be towards more established operational limits.

As mentioned in Chapter 3, there are no comprehensive datasets against which it is possible to validate the results of this thesis. Therefore, trust in the validity of the proposed models is based on previously established validation of each of the employed sub-components, and the assumption that combination of components is reasonable for the presented applications. It is evident that this is an issue, making it an open question if there are aspects of the results that are not accurate. Maybe some fish farmers possess suitable datasets that could be used to validate the compositions proposed in this thesis, but I have not been able to identify or collect them.

Solving problems requires a problem definition and a solution method. Solution methods are often what is in focus, and rightfully so because this is where the actual improvement from the state of the art can be made. However, it is in the problem definition that relevance to the real problem is determined. Solving the wrong problem in a smart way is not very useful. Validity of proposed solution methods in this thesis is extensively argued for in their respective research papers. For instance in paper 2, with comprehensive testing of case studies and comparison of the ALNS with best bound found by the commercial solver. That is, I am confident that the solution methods provide good results for the described problems. Validating problem definitions is harder, and even though I believe we have made reasonable choices in modeling and have managed to capture the main aspects that should be included, it is possible that others with better knowledge of the industry would see things differently.

In sum, the given discussion on validity covers both arguments for why the results are valid and reasons why caution should be considered when translating findings and insight to other applications or for use in decision making. Overall validity of problem, methods, models, and insight is considered to be good, with respect to the intended context.

5.2 Impact of research results

Identified implications from the research project are discussed in relation to industry practices, research in academia, authorities and regulations, and the expansion of exposed aquaculture. The topics are discussed separately in that order. In addition to the impacts presented here, it is expected that stakeholders can find additional use of project results since this is an exercise of identifying opportunities based on both industry knowledge and creativity. Therefore, people with different backgrounds may find different implications.

5.2.1 Industry practices

Relevant industry actors include fish farmers, shipping companies, ship designers, equipment companies, and service providers. Methods and insight on the effect of metocean conditions on vessel and fleet performance can be used in the design phase to identify necessary changes to fleet composition and vessel designs. For instance checking if an insufficient performance in a metocean condition can be solved by adding a vessel with the appropriate characteristics or by changing the design of a vessel. Effective changes to designs or compositions require identification of the bottlenecks limiting operation. This can be, for instance, sailing speeds, capacities, or operational limits. All three of which, and especially the latter two, might be possible to solve by changing the equipment onboard the vessel. It is even possible for equipment manufacturers to evaluate operational limits of vessels using their equipment and present it as a sales argument to vessel designers and shipping companies. Results of paper 5 indicate that relatively small differences in operational criteria can lead to significant gaps in susceptibility to weather induced delays. Such variations can result from both vessel response characteristics and equipment. Susceptibility to weather induced delays is also of interest for fish farmers when placing new fish farms or chartering vessels and can further be used by shipping companies in determining vessels and fleet composition based on their client base. That is, shipping companies or fish farmers that own vessels can adapt their fleet to best suit the operating environment at a set of fish farms, even considering the correlation in metocean conditions between fish farms.

Results on routing can enable shipping companies to explore new business models for utilization of their fleets, for instance, committing to providing a service level to fish farmers on a subscription rather than time charter. Currently, schedules are made for individual vessels meaning that the potential benefit of being part of a fleet is not exploited. If vessels in a fleet have no overlapping capabilities, this is not an issue. However, even if no more than two vessels that serve the same customer have one overlapping capability, there is potential for synergies in operating the vessels as a fleet rather than individual vessels. This is also a possibility for fish farmers scheduling the operations of a fleet of either owned or chartered vessels. Naturally, there are factors complicating the exploitation of this synergy in practice such as the short lead time for operation requests or needs not being announced until a vessel happens to be in the vicinity. However, it would probably still provide an improvement, and the mentioned factors can be adapted if there is will.

Considering susceptibility to weather induced delays as decision support when determining fleet composition can also have positive implications for safety of crew. If there is a probability that a vessel will perform a task even if metocean conditions are too rough, for instance due to perceived pressure to complete tasks within schedule, having considered the metocean conditions at locations when determining the fleet can help reduce the likelihood of having such situations. This is because decision makers are more likely to select vessels that are better suited to the environment they operate in. As a result there will be lower risk of accidents, higher quality on executed work, and more efficient work - assuming all weather impacts operations, with rougher weather having larger effects. On the other hand, “over-optimization” can make plans vulnerable to unforeseen events and deviations. For instance, minimizing redundancy, slack, and excess capacity can result in difficulties in adapting to even small changes. Therefore, it is important to remember the inherent uncertainty and the underlying needs of the industry, so that one is not simply solving theoretical exercises.

Routing of vessels can both improve costs, performance, emissions, and safety, but not necessarily all at the same time. Improved routing is primarily a tool for using vessels according to, or more in line with, the objectives of the operator or company. If the goal is, for example, to reduce greenhouse gas emissions, reduce sailing, or even distribution of workload between vessels, an optimization heuristic is a helpful tool.

It is in the interest of fish farmers to have better estimates on expected losses for accidental or unwanted events, like HABs. The presented method for assessing fish welfare emergency response is a first step towards risk assessments and management of emergency response measures for fish welfare emergencies. However, implementation and use of the method is not straight forward as it is not properly adapted for commercial use and thus requires special competence.

5.2.2 Regulatory bodies and authorities

The most obvious implications with respect to regulations originate from paper 1 and paper 3, covering greenhouse gas emissions and emergency preparedness. Both present methods that enable more realistic and accurate regulations on emissions and preparedness. From paper 1, the presented method could aid authorities and businesses in their work towards reduction of greenhouse gas emissions. It is indicative in quantifying the cost of proposed reductions in greenhouse gas emissions, enabling both policy makers and businesses to make the right decisions based on a broader assessment. Paper 3 enables functional evaluation of emergency preparedness for fish welfare emergencies. Such methods for quantifying estimates on the effect of measures, either for emission control or preparedness, enable authorities to transition from descriptive to functional requirements in regulations. This means that accuracy of regulations and incentives can be improved, which in addition is likely to entail better engagement from industry because they see that regulations are reasonable, targeted, and effective.

There is also an argument to be made that the focus on operational limits, and methods showing how this is used in optimal routing and scheduling of vessels, can raise the discussion on operational limits in the industry. Currently there are no regulations or industry standards on how to set or comply with such limits. Some companies have implemented simple rules for some operations and at some fish farms, however, in offshore O&G, operational limits are strictly and thoroughly regulated (DNV, 2011).

5.2.3 Academia

The fish farming industry can be described as somewhat conservative and largely experience-based. However, SFI EXPOSED is an example of willingness and desire in the industry to implement new technological solutions and creating closer ties with researchers and academia. In a sense, the industry is transitioning from experience-based to research-based development.

The industry has unique characteristics both regarding operating conditions and the framework they operate within and current practices. This thesis describes fish farming in a way that is useful for academics and researchers, in the research areas relevant for vessel operations, such as describing metocean conditions, vessel design and responses, fleet composition, and routing and scheduling. It also describes and links different fields of research, presenting state of the art literature and putting it in the context of fish farming. This contributes to establishing an understanding of the problems and system behavior for other researchers to build on. This encompasses both application of established method in fish farming context, making other researchers aware of the industry, and proposing how methods can be adapted. In addition, availability of information on the industry with its practices and problems has been limited, maybe especially for international researchers, but also for Norwegians. Even though collection and sharing of data still can improve, this thesis helps by publishing discussions on relevant topics. Bringing fish farming to the state of the art, and publishing research on the application hopefully contributes to more researchers picking up on the challenges raised in this thesis. so that the industry can benefit from advances in other industries on relevant fields.

5.2.4 Exposed aquaculture

Finally, this section presents four main implications related to the expansion of exposed aquaculture.

Implication 1: As authorities might establish strict functional requirements for emergency preparedness for offshore aquaculture this will entail a need for methods estimating performance for demonstrating compliance (Norwegian Ministry of Trade Industry and Fisheries, 2022). The presented methods contribute to enabling such compliance, and thus towards offshore aquaculture. Accurate evaluation of emergency preparedness is likely to be a prerequisite, as well as self-sufficiency for most types of emergencies. Fish farmers then have to argue that their solutions meet the requirements. Providing an analysis of the type presented in paper 3 can be useful to support that argument. In addition, the method can be used by fish farmers to assess risk of economic losses related to emergencies, which helps make informed decisions on emergency preparedness to achieve desired risk levels.

Implication 2: Enabling efficient vessel fleet compositions and utilization, improving cost and performance of vessel operations. Cost and availability, that is, ability to provide a satisfactory service level to fish farms, is a barrier to exposed aquaculture. Presented methods allow for finding better solutions than previously possible with respect to composition and routing, opening for available and safe operation in more exposed areas. For example, variations in exposure levels and correlation between fish farms can open for having only one or a few vessels with improved operational limits, given smart routing of vessels based on their specific characteristics.

Implication 3: Knowing that "exposed isn't exposed". That is, metocean conditions are complex and it can be beneficial to seek to establish certain relations between metocean conditions at different fish farms. For instance, it might be smarter to have one fish farm exposed to eastern waves and one to western rather than both being exposed to the same. Or the opposite might be true. Even if all fish farms are exposed, exact characteristics of metocean conditions can have an impact on fleet performance. Presented methods, especially from paper 4 and paper 5 can help investigate these aspects.

Implication 4: Not putting vessels in risky situations. As the industry expands in exposed areas, it is likely that vessels more often will operate close to their operational limits. Implementing sets of operational limits for vessels can make routing problems harder. Presented routing heuristics and knowledge about how metocean conditions affect fleet performance can aid shipping companies and fish farmers in achieving efficient routing while considering operational limits. This means that vessels are sent to operations not only based on a match in functionality, but also based on a probability that metocean conditions will exceed operational limits of the vessel for the considered operation. This enables decision makers to minimize occurrence of situations where crew feel pressure to operate in excessive metocean conditions - simply due to the fact that vessels are less likely to be put in such situations.

5.3 Applied research and fieldwork during a pandemic

During the first part of the research project and towards end of 2019, time and effort was put into establishing contacts in the research community around SFI EXPOSED and industry actors, with focus on preparing visits and field trips. Valuable trips were performed during the summer of 2019, however, the advent of the covid-19 pandemic effectively resulted in cancellation of all plans for further trips and made it impossible to make plans in which this type of interaction with and support from the industry were integrated. Naturally, this had a negative effect on the project as more field trips could have contributed to not only achieving a certain level of insight quicker, but also to reach a higher level. This is especially true for topics such as how the broader system functions, for instance how decisions are made and on what basis. In addition, more field trips and visits into 2020 could yield a better and earlier understanding of where and how this research project could maximize contributions towards development of the industry into exposed aquaculture. Initially, a substantial part of the project was to concretize the direction of the research both with respect to research objectives and, for instance, selection of case studies to investigate. This was based on how I perceived challenges and opportunities in the industry and how I believed this project could contribute. Four years is not a long time in research, and for a PhD-project this means that it is necessary to focus the research and aim for a delivery after about two years. That is, at some point focus must be shifted from exploration to execution or problem solving, and decisive choices for where to direct time and effort should be determined. In that context, 2020 was an important year for this project, however, it did not turn out as I hoped for, and this undoubtedly influenced the remaining work. It is not possible to describe in detail what was missed and how it would impact the research, plans were not completed for the whole year, and there is always uncertainty in the outcome of research activities. However, based on the experience and benefit of the field trips in 2019, there is little doubt that additional trips in 2020 following up on attained insight and knowledge would also be valuable. For example, in addition to already mentioned Mowi, FSV, and Frøy, a good dialogue was established with service vessel company AQS, and a visit was made to vessel designers Marin Design and the shipyard Moen Verft 2019. Some contact was maintained over phone and digitally through the pandemic, but this cannot make up for lost visits.

The fish farming industry can be characterized as conservative with owners and top management who have seen great success over the past decades with traditional methods. It is important to understand the reasons for and respect current practices in order for your ideas and input to be recognized as an outsider. Communicating understanding of practical limitations, and in that exercising a presence “on the floating collar”, is necessary to transfer knowledge back to industry. That is, being credible in disseminating research results and how those can be utilized and impact individual stakeholders. Even though I sought industry journals for publication of research papers, it is more fruitful to address industry actors more directly and discuss how results apply to them, and what impacts can be reaped.

6 Conclusion and further work

This chapter presents a summary of the accomplishments of the research project with respect to the research question and significance for stakeholders in fish farming. Focus is on vessels and vessel operations in the context of expansion of the industry towards exposed aquaculture. In addition, recommendations are given for further work related to the topics of this thesis.

6.1 Conclusion

The goal of the research project was to contribute towards available and safe vessel operations in exposed fish farming. Primarily, this covers the need for an understanding of how individual vessels and fleets of vessels can operate efficiently within the limitations given by challenging metocean conditions and constraints related to various operations. In the expansion towards more exposed fish farming, consideration of the relation to more sheltered farms must also be included. A diverse set of vessel types, locations, and operations must be coordinated in a purposeful manner. The thesis covers a review of state of the art from research areas and topics relevant for developing methods and models contributing towards the research goals. This covers description of metocean conditions, how they affect fish, vessels, and fish farms, design and operation of vessels, and urgent needs and emergency response. Important research gaps were identified on how effects on performance play out when considering a fleet of vessels and groups of fish farms. Extensive research is available on effects on behavior for individual vessels, and in operations research for other maritime industries, but fish farming application entails distinctive challenges that require bespoke studies and methods. The research project has resulted in five contributions that respond to precisely those gaps:

C 1 Framework for assessing the suitability of service vessels in a network of fish farms

C 2 Insight on the effects of the weather in a network of fish farms on service vessel fleet efficiency

C 3 Solution methods for routing and scheduling of service vessels

C 4 Methods for evaluating the performance of a fleet in a scenario

C 5 Method for assessing fish welfare emergency response capabilities and capacities

In line with the objectives of SFI EXPOSED, major implications of the research project are found for industry actors such as fish farmers and service suppliers. Improved understanding and methods for fleet composition and operations planning are beneficial for both safety and efficiency in exposed fish farming. For authorities, presented methods enable estimation of performance related to emissions and preparedness, and thereby enable more realistic and accurate regulations by supporting functional requirements. A significant implication of the research project towards academia is the description of the industry specific problems, making the area more accessible to other researchers, and hopefully more studied in the future. Finally, the project has also demonstrated that significant detail and precision is necessary in description of conditions, when considering effects on vessel fleet performance. In short, exposed isn't a single metocean condition.

Methods presented in this thesis represent new ideas, or application of established concepts in a new context. This is the first comprehensive study of aquaculture support vessels regarded as a fleet and provides insight on how to adapt and optimize vessel fleet and vessel operations in diverse and challenging metocean conditions. This thesis is a significant contribution towards safe and efficient vessel operations at exposed fish farms.

6.2 Further work

Proposals for further work cover both what can be continuations of this research project and what related research gaps that remain to be explored. A natural place to start is by refining the models or adapting them to specific cases and perform studies to identify more correlations that could be of interest to decision makers and designers in the industry. More studies on how changes in fleet composition affect fleet performance for different metocean conditions, for example, more variations in metocean conditions, differences in sailing speed, operational limits, and diversity in capabilities between the vessels, and the number of vessels of each type.

Methods and models for optimizing fleet composition and utilization, and performance assessments for emergency preparedness can give significant and immediate benefits to the industry. It would be useful to establish a method for routing of vessels considering both regular operations and emergency preparedness. That is, optimizing everyday routing and scheduling while considering the effect on emergency preparedness when vessels are used for both normal operations and emergency response. In addition, improving the proposed methods to a commercial level should be considered, as they enable maximization of service level to fish farms and utilization of vessels which in turn can reduce costs related to acquisition and operation of aquaculture support vessels. The next steps should be engaging industry in further development and performing case studies to demonstrate usefulness and validity.

Let's try it!

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Appendix A: Research papers

Research paper 1

Cost-emission relations for maritime logistics support in aquaculture
Slette, H.T.; Asbjørnslett, B.E.; Fagerholt, K.
Journal of Physics: Conference Series, Vol. 1357, 2019

Journal of Physics: Conference Series

Cost-Emission Relations for Maritime Logistics Support in Aquaculture

To cite this article: Hans Tobias Slette *et al* 2019 *J. Phys.: Conf. Ser.* **1357** 012029

Cost-Emission Relations for Maritime Logistics Support in Aquaculture

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Abstract. This paper presents a method for evaluation of the economic cost of reducing the emissions from a fleet operating in the aquaculture industry. The method accounts for the fact that different fleet compositions perform differently in a given operating environment. A simulation model tests the fleets, returning the achieved mission coverage, total operating cost and emissions. The cost and emissions for each fleet are adjusted for coverage before their relations are analyzed using regression on the Pareto frontier. A case study is performed, estimating the cost of 5%, 10%, 20%, 50% and 100% reductions in CO_2-emissions from well boat operations.

1. Introduction

The main purpose of the aquaculture industry is the farming of aquatic species. Various aquaculture activities such as ocean farming of Atlantic salmon requires the use of vessels to support the production at the sites. Some vessels transport biomass and consumables, others function as work platforms for the execution of operations on the locations. In the case of fish farming well boats carry live fish, delouse fish and sort fish, feed vessels deliver fish feed to the sites, and service vessels perform IMR and other necessary operations. A fleet of vessels serving a set of locations performs the maritime logistics support for that sea-based aquaculture system. The operational performance of the maritime logistics support is determined by its ability to execute the requested operations in the system within reasonable time. Other aspects of the marine logistics support to be considered include safety, fish welfare and pollution, especially greenhouse gas emissions.

Reductions in greenhouse gas emissions are desired in all industries, but to what degree measures are taken depends on the economic consequences. Studies on the effects and selection of measures in the maritime context include [1] and [2]. Measures may also affect the vessel operations e.g. through reductions in cargo space or range. A meaningful comparison of emission reducing measures with respect to cost should therefore consider the effect on the vessel performance. The method presented in this paper tests fleet compositions in a given operating environment and adjusts their total cost and total emissions based on the achieved operational performance.

2. The Method

The basic idea of the method is to compare the operational costs and emissions of a set of fleets which perform equally well with respect to mission demand. Operational costs and emissions are found by simulating the operations of all fleets, in a defined operating environment over a given time period. A flowchart describing the method is shown in Figure 1. A vessel routing heuristic is built in to the simulation model, planning the operations of the vessels for the next planning period, with regular intervals throughout the simulation. In every planning process the heuristic analyses the mission requests from the operating environment and seeks to cover all missions with minimum cost. The aspect of operability of marine operations, both in execution and planning, is inspired by [3], and the work of [4] from the offshore wind industry. While the routing heuristic is based on the ideas presented in [5] and [6].

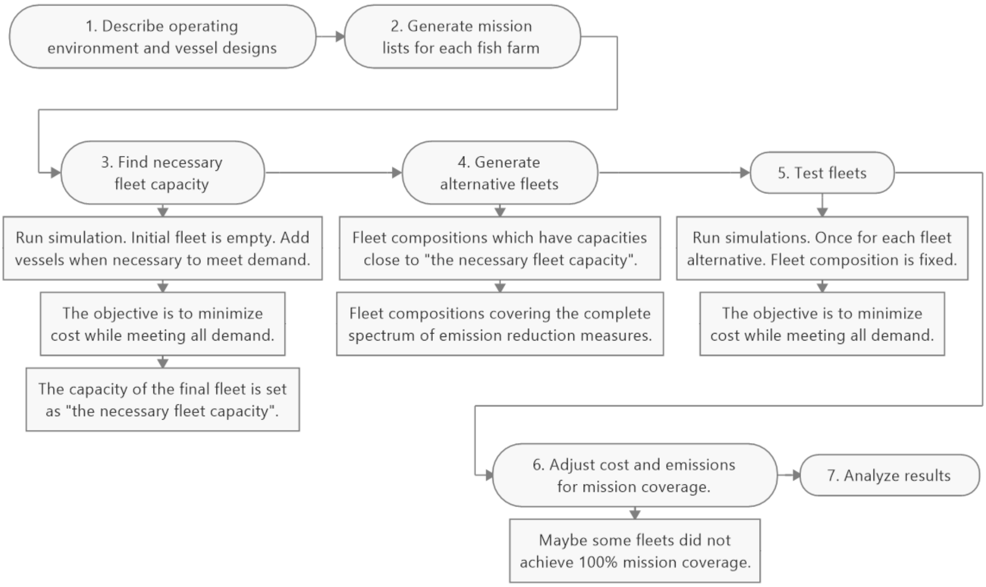

Figure 1. Flowchart describing the main steps of the method.

2.1. *Testing fleet compositions*

The method can either test for a set of predefined fleets, or for a set of available vessel designs. In the latter case an initial procedure is run, generating alternative fleets with the necessary capacity to cover the mission requests of the operating environment. This capacity is found by running the simulation with a modified version of the routing heuristic. It starts the simulation with an empty fleet and adds vessels to the fleet during each planning process, if it is necessary to cover the requested missions. At the end of the simulation, the heuristic has composed a fleet with enough capacity to cover all requested missions. Having the capacity, alternative fleets are generated randomly from the set of available vessels. However, it is ensured that the generated fleets cover the whole spectrum of available emission reduction measures. That is, some fleets have no measures implemented on any vessel, other fleets have "all" measures implemented on all vessels, while most fleets lie somewhere in between.

All fleets are tested for the same realizations of the stochastic environmental variables to isolate the effect of the differences between the fleets. For each fleet, the achieved mission coverage, total cost and total emissions are returned. Based on the output, the expected total cost and total emissions corresponding to 100% mission coverage are derived for each fleet.

The resulting data set contains an approximation of the cost-emission relation, adjusted for mission coverage, for the set of available vessel designs in the given operating environment. In order to calculate the economic cost of relative reductions in emissions, first the basis fleet must be selected. In a general study of the cost-emission relation, the most cost-efficient fleet is selected as the basis. If all potential fleets have been evaluated, the cost-emission relation is constrained by the resulting data set entries. That is, e.g. interpolation between two entries on the Pareto frontier does not make sense if there are no fleet alternatives populating those areas. However, if the set of possible fleet compositions far outnumbers the tested set, there is a possibility that the Pareto frontier is more densely populated, and thus, interpolation could be defended.

3. The Case Study

The case study covers well boat operations in three cases of different sizes. The purpose of the study is to present an example of the application of the method. The goal of the study is to estimate the relative cost of 5%, 10%, 20%, 50% and 100% reductions in CO_2 emissions from well boat operations.

3.1. Setup, assumptions and simplifications

The three cases differ in the number of fish farms, hatcheries, slaughterhouses and ports, as presented in Table 1. Fish farms are described by the size of the farm, the position and the weather at the location. Size is given by the number of cages and is drawn from a uniform distribution between 4 and 10. All cages are identical and have a capacity of 200 000 fish. Smolt is delivered at 100grams and fish is collected for slaughter at 5kg. The mortality rate is set to 0%, meaning that a cage receiving 20 tons of smolt delivers 1000 tons of fish to slaughter.

Table 1. Case descriptions. The cases are identical with respect to all other aspects than the ones presented here.

Case	Fish farms	Hatcheries	Slaughterhouses	Ports	Area (km^2)
1	10	1	1	2	5 000 (50x100)
2	20	1	2	4	10 000 (50x200)
3	40	2	3	8	20 000 (100x200)

Common for all hatcheries, slaughterhouses and ports is that they have no capacity limitations, both regarding processing and the number of vessels to accommodate at the same time. Hatcheries provide smolt, slaughterhouses receive fully grown fish for slaughter, and ports provide the well boats with any necessary equipment.

Missions are defined by type and scope. The mission types are presented in Table 2 with corresponding operation rates and operational limits for each vessel size (see Table 3). Mission scope is determined by the biomass at the fish farm – all missions cover all biomass. For each farm, a mission list is generated based on distributions for intergeneration times for each mission type, and the causal dependencies between the mission types. First, a time is drawn for the first delivery of smolt, starting the first production cycle, then a time is drawn for the collection of fish for slaughter. During the period between smolt and slaughter, delousing and sorting operations are performed. At the end of the production cycle, after the fish is collected for slaughter, there is a quarantine period before new smolt can be delivered. The scope of the smolt delivery may cover any integer number of cages, from 1 to the number of cages at the fish farm.

Table 2. Vessel sizes, mission types, operation rates and operational limits.

	Small vessels		Medium vessels		Large vessels	
Mission types	Rate (tons/h)	Limit	Rate (tons/h)	Limit	Rate (tons/h)	Limit
Transport smolt	50	2	75	2	100	3
Delousing 1	50	2	75	2	100	2
Delousing 2	200	2	300	3	400	3
Sorting	50	2	75	3	100	3
Transport slaughter	100	2	150	2	200	3

Each fish farm experiences unique weather. Whether a mission can be performed or not depends on the combination of the weather and the relevant operational limit for the vessel in question. In this case study the weather state is described by one parameter ranging from 1 to 5, corresponding to perfect and terrible weather, respectively. An operational limit of 2 means that the vessel can perform the operation in weather state 1 and 2 conditions.

In addition to vessel size (see Table 3), vessels are defined by design speed (see Table 4) and fuel type (see Table 5). Cargo space loss related to lower energy density fuels or more space demanding propulsion systems is not considered in these problem cases, neither is refueling. Choice of design speed and fuel type affect the CAPEX, in terms of relative change from the base vessels presented in Table 3. An increase in vessel design speed requires an increase in installed power, which in turn leads to higher propulsion installation costs and CAPEX. The same argument is made for the choice of fuel type, propulsion systems based on LPG, LNG, Hydrogen and Electricity are assumed to be more expensive to purchase and install than such based on HFO and MDO. These choices also affect cost through fuel consumption, however this expense depends on the energy consumption of the vessel, which is calculated based on the operating states of the vessel. During transit the energy consumption rate is 75% of installed power, 30% while waiting on weather on location and 20% during operations support.

CO_2 emissions are calculated from the energy consumption, using a factor describing the CO_2 production per consumed kWh of fuel, depending on the fuel type (see Table 5).

Table 3. Base vessel types. All vessels in the case study are variations of these base vessels.

Vessel Size	Volume (m^3, tons)	CAPEX ($/day)	Speed (kn)	Power (kW)
Small	1000, 150	2877	10	1000
Medium	2000, 300	4795	11	1450
Large	3000, 450	6712	12	2100

Table 4. Vessel speed variations and the resulting effect on installed power, and therefore also on CAPEX.

ΔSpeed (kn)	ΔPower (%)	ΔCAPEX (%)
-2	-6	-6
-1	-4	-4
0	0	0
+1	6	6
+2	14	14

Table 5. Fuel type variations.

Fuel type	Efficiency (kWh_{output}/kWh_{fuel})	CO_2 (kg/kWh_{fuel})	Price ($/kWh)	ΔCAPEX (%)
HFO	40%	0.27	0.04	0
MDO	40%	0.25	0.055	0
LPG	40%	0.22	0.085	5
LNG	40%	0.18	0.01	10
Hydrogen	45%	0	0.285	15
Electricity	75%	0	0.20	20

The routing heuristic is set to re-plan vessel assignments every 7 days, and plan for all missions that start within 14 days. A total of 500 alternative fleets are tested for each case, with each test covering 1000 days of operation.

3.2. Results

With 90 available vessel types and relevant fleet compositions having from 4 to 15 vessels, it may be appropriate to assume that there are fleets populating the Pareto frontier that are not tested. Based on this assumption the cost of a relative reduction in CO_2 emissions can be approximated by the intersections between the relevant CO_2 emissions and the Pareto frontier (see Figure 2). For each case, the cost of reductions in CO_2 is found by using the most cost-efficient fleet as the base and using piecewise linear regression on the Pareto frontier. Total cost and total emissions are adjusted by division on the achieved mission coverage.

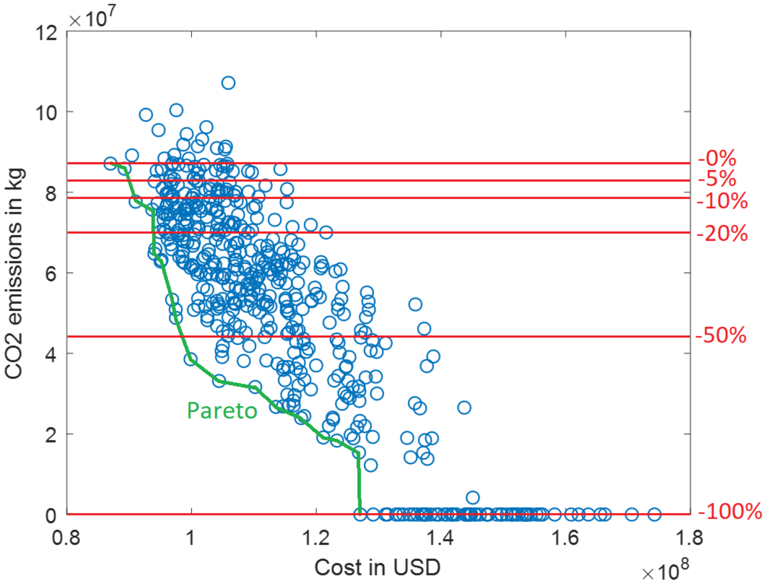

Figure 2. Cost-emission relations for case 3, adjusted for achieved mission coverage. Including stepwise linear regression on Pareto frontier and lines for relative reduction in CO2 emissions.

The costs of the relative reductions in CO_2 emissions for all three cases are presented in Table 6.

Table 6. Analysis results. The cost of relative reductions in CO2 emissions in %-change and absolute change compared to the most cost-efficient fleet composition for each case.

	Cost (Relative, USD)		
Reduction	Case 1	Case 2	Case 3
5%	11.3% , 4.013e+06	14.9% , 1.143e+07	03.4% , 2.930e+06
10%	16.7% , 5.943e+06	15.6% , 1.194e+07	04.5% , 3.880e+06
20%	20.0% , 7.093e+06	16.6% , 1.273e+07	07.9% , 6.900e+06
50%	29.7% , 1.054e+07	36.0% , 2.751e+07	13.5% , 1.171e+07
100%	31.1% , 1.105e+07	39.4% , 3.011e+07	46.1% , 4.011e+07

4. Discussion

As could be expected, the results indicate an increasing cost for greater relative reductions in CO_2 emissions. For Case 1 and Case 2, even a 5% reduction in CO_2 emissions is relatively costly at 11.3% and 14.9% cost increase, respectively. For Case 3, the cost is much lower at 3.4%. From the case study it is hard to identify a general cost-emission relation across the test cases. There is no apparent way of deriving the results of Case 3 based on the results of the two other cases and the known differences between the cases. This finding supports the hypothesis that a simulation-based approach is beneficial for studying these relations.

A potential source for error is the assumption on the position and shape of the Pareto frontier. While the assumption of more fleets populating the Pareto frontier is supported by the high number of untested fleets, the certainty of the position of the Pareto frontier is not. However, the clustering of the tested fleets in Figure 2 may indicate that it is unlikely that the true frontier is substantially different from the test results.

Other sources of error related directly to the execution of the case study relate to the simplifications made in defining the operating environment, the vessels and their operations. An example is the calculation of energy consumption and CO_2 emissions not considering that machinery efficiency and CO_2 production depends on machinery load. Another example is that cargo space loss related to the choice of fuel type is not included, however this can be included by changing the vessel designs included in the case. Despite the simplifications, it could be argued that the effect is limited because the case study compares the fleets rather than seeking to identify the exact performance of a single fleet. As such, if the simplifications have a similar impact on all tested fleets, the effect on the final result may be insignificant.

The model allows for other emission reduction measures to be included, provided that the measures can be described in terms of the parameters of Table 3, Table 4 or Table 5. A better hull shape, improved propeller design or a more fuel-efficient propulsion system running on the same fuel type, are examples of such measures that can be included. In terms of the vessel parameters, the effect will be increased CAPEX, reduced power demand and increased efficiency. Further, the model allows for inspection of the cost utility of different measures. The results of all fleets are logged making it possible to see what measures were implemented by which fleets. This way the effect of e.g. speed reductions on cost and emission can be isolated by identifying otherwise similar fleets with changes in design speed.

The presented method could aid authorities and business in their work towards making the industry greener. It is indicative in quantifying the cost of proposed reductions in greenhouse gas emissions, enabling both policy makers and businesses to make the right decisions based on a broader assessment.

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Research paper 2

The Aquaculture Service Vessel Routing Problem with Time Dependent Travel Times and Synchronization Constraints
Lianes, I.M.; Noreng, M.T.; Fagerholt, K.; Slette, H.T.; Meisel, F.
Computers & Operations Research, 134 (2021) 105316

Computers & Operations Research 134 (2021) 105316

Contents lists available at ScienceDirect

Computers and Operations Research

journal homepage: www.elsevier.com/locate/cor

The aquaculture service vessel routing problem with time dependent travel times and synchronization constraints

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ARTICLE INFO

Keywords:
Maritime transportation
Routing
Synchronization
Time dependency

ABSTRACT

This paper studies the Aquaculture Service Vessel Routing Problem (ASVRP), which is an important planning problem arising in sea-based fish farming. In the ASVRP, there is a set of fish farms located in the sea, where each fish farm has one or more service tasks to be performed by a given heterogeneous fleet of service vessels with different capabilities. Some service tasks require simultaneous operation of more than one vessel and might also have time windows and precedence requirements. Furthermore, varying weather conditions make the sailing times and the service times of the tasks time dependent. The objective of the ASVRP is to maximize the value of the service tasks performed within a given planning horizon. We propose a time discrete optimization model for the ASVRP, formulated as a time dependent, prize collecting vehicle routing problem with synchronization constraints and time windows. Furthermore, we present an Adaptive Large Neighborhood Search (ALNS) heuristic for solving the problem. Results on a number of test instances based on real world data show that both the ALNS heuristic and a commercial solver are able to find high quality solutions for small problem instances, while the ALNS heuristic is superior when the problem size increases.

1. Introduction

Sea-based fish farming (aquaculture) is an industry which has experienced significant growth over the past decades, resulting in a total production of 110.2 million tonnes worldwide in 2016, making up 46.8 % of the combined production from capture fisheries and aquaculture (FAO, 2018). In Norway, more than 1000 fish farms cover the coastline, with the industry being the third largest exporter (Misund, 2019) and an important source of income for many coastal communities (Bjelland et al., 2015). By 2050, the annual production volume in Norway is expected to reach five million tonnes, up from 1.5 million tonnes in 2019, provided that key production and environmental challenges are resolved (Bjelland et al., 2015).

The complexity of aquaculture logistics has increased alongside the growth of the industry due to a larger number of fish farms, more exposed locations and consolidation of actors into larger firms controlling a greater part of the value chain. This has resulted in a need for innovative solutions for improved planning. One of the highlighted research topics is service vessel logistics, seeking to reduce costs, improve system reliability and preserve end product quality, even with an increased service demand at exposed locations (Bjelland et al., 2015). The service vessels perform service operations or tasks at the different fish farms, such as installations, inspections and maintenance, delousing and general support. These service tasks are essential both to maintain desirable fish health and to prevent damage of the farms, and the potential consequences of failing to achieve any of these involve the risk of both high economical losses and environmental pollution. Furthermore, these operations are often intricate and sometimes made difficult by challenging weather conditions.

1.1. Problem description

We consider a real life short-term planning problem arising in sea-based fish farming, which we denote the Aquaculture Service Vessel Routing Problem (ASVRP). In the ASVRP, there is a set of fish farms located in the sea, where each farm has one or more service tasks to be

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https://doi.org/10.1016/j.cor.2021.105316
Received 2 October 2020; Received in revised form 1 April 2021; Accepted 1 April 2021

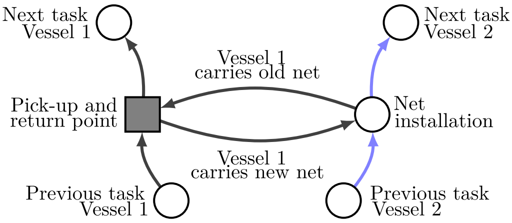


Fig. 1. Precedence and synchronization exemplified by net operations. Vessel 1 picks up a new net and then transports it to the location. Upon arrival it is joined by Vessel 2. The vessels perform the net installation together before Vessel 1 transports the old net to the return point.

performed by a given heterogeneous fleet of service vessels. The vessels are defined by their capabilities and characteristics (e.g. size, sailing speed, fuel consumption and equipment). The vessels' capabilities and characteristics affect sailing cost and operational agility, which again restricts which service tasks a vessel is capable of performing.

The service tasks can be very different from each other for example with respect to service duration, which depends on both the vessel type performing the service and the task's operation type, as well as the weather conditions. The operation type determines a task's importance and urgency, the required vessel capabilities, and if there are any special requirements such as *precedence* and *synchronization*. Precedence means that one task must be completed before another can commence. For example, the task of transporting a new net to a fish farm holds precedence over the task of installing the net. Meanwhile, net installation requires two vessels to complete it. In that case, both vessels need to perform this task simultaneously in order to complete the net installation, which give synchronization constraints. Furthermore, net installation holds precedence over returning the used net. This example is illustrated in Fig. 1, where vessel 1 sails from the location of its previous task, picks up a new net and then transports it to the fish farm where the net is going to be installed. Another vessel, vessel 2, performs the net installation simultaneously with vessel 1. Vessel 1 then returns the used net before sailing to the location of its next task whereas vessel 2 goes to its next task directly after finishing the net installation. There also exist service tasks requiring heavy equipment or certain capabilities, which only some large vessel types have. Alternatively, some of these tasks can be split into smaller ones and completed by multiple smaller vessels instead of one large. Such tasks are referred to as *consolidated*. If such a consolidated task is serviced by more than one vessel, it will again require synchronization of all involved vessels.

Both the sailing times and service times of the tasks are affected by the weather conditions. The duration of a service task increases in bad weather and may even be postponed in anticipation of better weather. Sailing also takes longer time in bad weather because the service vessels usually follow a constant power policy, and the resistance increases in harsh weather. Increased sailing times thus also lead to increased sailing costs. Therefore, the weather forecast for the next few days is a necessary prerequisite to the ASVRP, so that good estimates on the time dependent durations and costs can be established.

Not all service tasks must be performed within the given planning horizon (typically a few days). Thus, the ASVRP consists of determining which tasks to be performed by which service vessel, in order to maximize the value of the service tasks minus the sailing costs of the vessels. We also need to determine the sequence of the service tasks for each service vessel, i.e. the route, as well as the start time of all tasks along the route.

1.2. Literature review

To the extent of our knowledge, the ASVRP has not previously been studied. The ASVRP is a rich routing problem that extends vehicle routing problem (VRP) in three main directions; the Prize Collecting or Profit Collecting VRP (PCVRP), VRP with synchronization constraints (VRPSyn) and Time Dependent VRP (TDVRP). Each of these has been well studied separately, and in the following we limit our literature review to these three routing problems.

Similarly to the ASVRP, the customer visits are not compulsory in the PCVRP, but a prize or profit can be collected from each customer when visited or serviced (Tang and Wang, 2013). Archetti et al. (2014) provide an overview of variants of vehicle routing problems with profits. They present models for the cases of a single vehicle and multiple vehicles in diverse variants. For each problem variant, relevant literature is discussed with a focus on the type of the proposed solution method, i.e., exact algorithm, heuristic algorithm, or approximation algorithm. The authors argue that future research should focus on problems with multiple vehicles and additional characteristics of real world applications, as is the case for the ASVRP that we investigate in this paper. Prize collecting pickup and delivery routing problems are often treated through arc-based model formulations, where an arc represents the service of pickup and delivery request and a prize is collected the first time that an arc is traversed by a vehicle. For this kind of problem, Black et al. (2013) propose a Variable Neighborhood Search and a Tabu Search that maximizes a profit function that involves collected prices as a proxy of revenue and travel times as a proxy of cost. A model variant with time-dependent travel times is also presented. Both models consider just a single vehicle in the routing. Hammami et al. (2019) investigate an arc-based mathematical formulation for a bid construction problem. In this problem, a carrier has to identify a set of most profitable transportation contracts to bid on. The problem is formulated as a profit collecting vehicle routing problem and bids can be derived from the resulting solutions. The problem is solved by an Adaptive Large Neighborhood Search (ALNS) that is extended by local search mechanisms and hybridized with a set packing problem that derives non-dominated solutions among a set of solutions obtained by the ALNS. A closely related problem is the team orienteering problem (TOP), which is basically a PCVRP with an upper limit on the total duration of the route. The problem was introduced by Chao et al. (1996) who also presented a two-step solution method consisting of a construction heuristic and an improvement phase that shifts customers and exchanges customers among routes. Different versions of the TOP have been solved by both exact (e.g. Assunção and Mateus, 2019; Hanafi et al., 2020) and heuristic solution methods (e.g. Amarouche et al., 2020; Archetti et al., 2007; Hammami et al., 2020). In the maritime context, the tramp ship routing problem with optional cargoes can be considered as a version of a price collecting pickup and delivery problem (e.g. Homsi et al., 2020).

The VRPSyn is a VRP where more than one vehicle (or any other resource) may or must be used to service a task and that the vehicles' service times must be synchronized, usually meaning simultaneous service of the task (Drexl, 2012). This causes the routes of the VRPSyn to be interdependent, meaning that a change in one route may affect other routes due to the synchronization. The literature on the VRPSyn covers multiple industries and problem areas, such as home care (e.g. Bredström and Rönnqvist, 2008; Mankowska et al., 2014; Frifita and Masmoudi, 2020), routing of technicians (e.g. Parragh and Doerner, 2018; Anoshkina and Meisel, 2020), routing workers to ground handling jobs at an airport (e.g. Fink et al., 2019), routing problems with two echelons (e.g. Grangier et al., 2016), aircraft fleet routing (e.g. Ioachim et al., 1999), and the full truckload pickup and delivery problem with resource synchronization (e.g. Grimault et al., 2017). Synchronization constraints are also relevant in some maritime routing problems, such as in project shipping where some cargoes are coupled and require synchronized deliveries (e.g. Andersson et al., 2011; Stålhane et al., 2015).

The TDVRP is a VRP where the travel times (and possibly also the service times) are dependent on when the trips are performed. In the ASVRP this happens due to varying weather conditions, whereas in land-based routing this is usually caused by varying traffic conditions (e.g. rush hours). Malandraki and Daskin (1992) present and discuss formulations, properties and heuristics for the TDVRP, while Ichoua et al. (2003) propose a model that satisfies the 'first-in–first-out' principle, meaning that a vehicle cannot arrive earlier by starting later. Dabia et al. (2013) develop a branch-and-price algorithm for the TDVRP with time windows, while Franceschetti et al. (2017) propose an ALNS heuristic for the time-dependent pollution routing problem. Ma et al. (2017) study a combined order selection problem (i.e. prize collecting) and TDVRP, which is solved by a hybrid ant colony and local search heuristic.

In contrast to the above studies the ASVRP combines features of all three fields, the PCVRP, the VRPSyn, and the TDVRP. It even involves further features such as compatibility relations between tasks and vessel, which are known from the routing of heterogeneous vehicle fleets, see Baldacci et al. (2008). Furthermore, while studies on the TDVRP merely consider time dependent travel times, the ASVRP also has time dependent service times. Another difference is that we in our paper use a time discrete model, which can also be well suited (Agra et al., 2013). Time discrete modeling approaches have also been used for maritime applications with time dependent travel times, although in a different context than the ASVRP and without features like synchronization of tasks, consolidated tasks etc. (e.g. Christiansen et al., 2017). Following the suggestions of Agra et al. (2013) and Christiansen et al. (2017), we use a time discrete model in this paper in order to easily handle the time dependent travel and service times and the synchronization of tasks.

1.3. *Contributions and paper outline*

This paper contributes to the research literature by 1) introducing and formally defining the ASVRP, 2) presenting a new time discrete optimization model for the ASVRP, and 3) proposing an ALNS heuristic for solving the ASVRP. The ALNS significantly extends previous ALNS heuristics to account for the additional complexity of the ASVRP. Each task inserted in a route is represented with both an earliest and a latest starting time, which are used to check the feasibility of insertions with regards to both the intra-route connections and dependencies between routes. Additionally, sets containing information about precedence and simultaneous tasks are introduced in the ALNS to maintain the synchronization constraints. Inspired from Liu et al. (2019), we have also implemented a new destroy heuristic, called synchronized removal, which removes all tasks bound by synchronization from the solution. Furthermore, we generate a number of test instances based on real world data from the aquaculture industry and show that both the ALNS and a commercial solver are able to find high quality solutions for small problem instances, while the heuristic is superior when the problem size increases.

The optimization model for the ASVRP is presented in Section 2, while Section 3 describes the ALNS heuristic. The computational study is presented in Section 4 and concluding remarks are given in Section 5.

2. Mathematical model

This section presents the optimization model for the ASVRP. Section 2.1 introduces the modeling approach and the notation used, while the model is presented in Section 2.2.

2.1. *Modeling approach and notation*

We have chosen to formulate the problem as a time discrete model, where the given planning horizon is divided into time periods of equal length. Each action started by a vessel (i.e. sailing, waiting or servicing a task) is associated with one such time period, and the duration of an action is measured in the number of periods. Each service task can only be started once, meaning that it cannot be partly executed and then left to be completed at some later time in the planning horizon. Tasks can be started at any time period within their specified time windows. In addition to the service tasks that need to be performed, we include a start task and a dummy end task for each vessel. The start task and earliest starting time of a given vessel corresponds to the location and time when the vessel becomes available after earlier assignments outside the current planning horizon. As mentioned in the problem description, the fleet of service vessels is heterogeneous. Note that since the vessels have different initial locations and times when they become available for servicing new tasks, even vessels of the same vessel type must be considered as different from each other. Moreover, the vessels are not expected to sail to a certain port after finishing their tasks, thus the dummy end task represents the vessel waiting at the last location visited after having finished all its tasks. The sailing to the dummy end task can start after the end of the planning horizon if the vessel has not completed its last task within the planning horizon. The sailing time to the dummy end node is always zero.

The notation used in the model is as follows.

2.1.1. *Sets*

$\mathscr{N}$	Set of all non-dummy tasks
$\mathscr{N}^T$	Set of all tasks, including dummy start and end nodes of all vessels v, $\mathscr{N}^T = \mathscr{N} \cup \{o(v)\} \cup \{d(v)\}$.
$\mathscr{K}$	Set of consolidated tasks, $\mathscr{K} \subseteq \mathscr{N}$.
$\mathscr{N}_k^C$	Set of all subtasks that constitute task k, $\mathscr{N}_k^C \subseteq \mathscr{N}$.
$\mathscr{N}^{\mathscr{S}}$	Set of single tasks that are neither defined as a consolidated task, nor a subtask that constitutes any consolidated task k, $\mathscr{N}^{\mathscr{S}} \subseteq \mathscr{N}$.
$\mathscr{N}_v$	Set of all tasks a vessel v can complete (compatibility relations), $\mathscr{N}_v \subseteq \mathscr{N}$.
$\mathscr{V}$	Set of all vessels.
$\mathscr{V}_i$	Set of all vessels that can complete task i (compatibility relations), $\mathscr{V}_i \subseteq \mathscr{V}$.
$\mathscr{T}$	Set of time periods within the planning horizon.
$\mathscr{T}_i^{TW}$	Set of time periods within the planning horizon where task i can be started, with E_i and L_i being the start and end period of the time window, i.e., $\mathscr{T}_i^{TW} = [E_i, E_i + 1, \ldots, L_i] \subseteq \mathscr{T}$.
$\mathscr{T}^E$	Set of time periods the vessels can sail to the dummy end node. This set includes all time periods in the planning horizon and additionally the T_{max}^O time periods following the end of the planning horizon.
$\mathscr{A}_v$	Set of arcs that can be traversed by vessel v.

2.1.2. *Parameters*

T_{vijt}^S	Number of time periods used to sail from task i to task j, for vessel v if it starts the sailing in time period t.
T_{vijt}^{SP}	Number of time periods vessel v uses to sail from task i to task j if it finishes the sailing in time period t.
T_{vit}^O	Number of time periods used by vessel v to service task i if it starts in time period t.
T_{vit}^{OP}	Number of time periods vessel v uses on performing task i if it finishes performing task i in time period t.
T_{max}^O	Number of time periods used to complete the task with the longest duration when started in the last period of the planning horizon.
T_v^B	Earliest starting time for vessel v.
C_{vijt}^S	Sailing cost from task i to task j for vessel v if it starts sailing in time period t.
B_{it}^T	Profit gained by starting task i in time period t.
P_{ij}	Indicates if there is a precedence requirement between two tasks i,j. It takes the value 1 if task i has precedence over task j, 0 otherwise.
S_{ij}	Indicates if there is a simultaneous requirement for two tasks i,j. It takes the value 1 if task i needs to be performed at the same time as task j, 0 otherwise.
N_k	The number of single tasks that constitutes task k. Equal to the cardinality of $\mathscr{N}_k^C$.

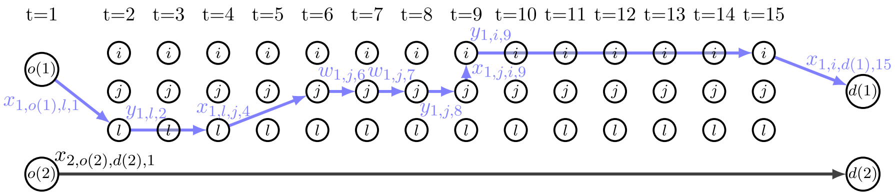


Fig. 2. Example of two vessels' flow in a time–space network. Vessel 1 starts in $o(1)$, with $T^B_1 = 1$, and ends in the dummy end task $d(1)$. The operations of vessel 1 have the durations $T^O_{1,l,2} = 2, T^O_{1,j,8} = 1$ and $T^O_{1,i,9} = 6$. Furthermore, $T^S_{1,j,i,9} = 0$, which means that the tasks i and j are at the same location. Vessel 2 is idle for the complete duration of the planning horizon, sailing directly from its start task $o(2)$ to its dummy end task $d(2)$, with $T^S_{2,o(2),d(2),1} = 0$.

2.1.3. Variables

x_{vijt}	A binary variable which takes the value 1 if vessel v starts sailing from task i to task j in time period t, 0 otherwise.
y_{vit}	A binary variable which takes the value 1 if vessel v starts performing task i in time period t, 0 otherwise.
w_{vit}	A binary variable which takes the value 1 if vessel v waits at task i in time period t, 0 otherwise.
z_i	A binary variable which takes the value 1 if task i is not started in the planning horizon, 0 otherwise.

The set of arcs vessel v can sail, $\mathscr{A}_v$, is limited to include only arcs between tasks vessel v is capable of performing while respecting time windows and precedence constraints. It is formally defined as $\mathscr{A}_v = \{(i,j) | i \in \mathscr{N}_v \cup \{o(v)\}, j \in \mathscr{N}_v \cup \{d(v)\} \wedge P_{ji} = 0 \wedge \exists t \in \mathscr{T}^{TW}_i | t + T^O_{vit} + T^S_{vijt} \leqslant L_j\}$, where condition $P_{ji} = 0$ ensures that j does not hold precedence over i. The last condition checks whether there exists a start time for task i that allows to reach task j before the end of j's time window. This check for compatible time windows only applies to non-dummy tasks.

The set $\mathscr{T}^E$ is the set of time periods the vessels can start sailing to the dummy end node. This set includes all time periods in the planning horizon and additionally the time periods used to complete the task with the longest duration when started in the last period in the planning horizon. The set is constructed to secure that vessels can start performing tasks even if they do not manage to finish within the end of the planning horizon.

The profit B^T_{it} is set with the assumption that a task is performed for the duration of the operation time T^O_{vit}, or for the remaining time periods in the planning horizon. This means that the profit of a task is equal for all the time periods where the vessel is able to complete the task within the planning horizon. In the case where starting task i in time period t results in only a fraction of the task being completed within the planning horizon, the profit B^T_{it} for this time period will reflect the fraction being completed.

The binary variables x_{vijt} and y_{vit} indicate whether a vessel v starts sailing or performing a task in time period t, respectively. However, the sailing or the task itself may take more than one time period. The waiting variable w_{vit} equals 1 for each time period the vessel is waiting before starting on task i. The use of the variables is illustrated in the time–space network for an example in Fig. 2.

2.2. Mathematical model

Based on the notation defined in Section 2.1, we can formulate the ASVRP as follows:

$$max\, z = \sum_{v \in \mathscr{V}} \sum_{i \in \mathscr{N}_v} \sum_{t \in \mathscr{T}} B^T_{it} y_{vit} - \sum_{v \in \mathscr{V}} \sum_{(i,j) \in \mathscr{A}_v} \sum_{t \in \mathscr{T}} C^S_{vijt} x_{vijt} \tag{1}$$

subject to

$$\sum_{(i,j) \in \mathscr{A}_v | T^S_{vijt} > 0} x_{vijt} + \sum_{i \in \mathscr{N}_v} y_{vit} + \sum_{i \in \mathscr{N}_v} w_{vit} \leqslant 1 \qquad v \in \mathscr{V}, \quad t \in \mathscr{T} \tag{2}$$

$$\sum_{v \in \mathscr{V}_i} \sum_{t \in \mathscr{T}^{TW}_i} y_{vit} + z_i = 1 \quad i \in \mathscr{N}^S \tag{3}$$

$$N_k = N_k \sum_{v \in \mathscr{V}} \sum_{t \in \mathscr{T}^{TW}_k} y_{vkt} + N_k z_k + \sum_{v \in \mathscr{V}} \sum_{i \in \mathscr{N}^C_k} \sum_{t \in \mathscr{T}^{TW}_i} y_{vit} + \sum_{i \in \mathscr{N}^C_k} z_i \qquad k \in \mathscr{K} \tag{4}$$

$$y_{vi(t - T^{OP}_{vit})} = \sum_{(i,j) \in \mathscr{A}_v} x_{vijt} \qquad \begin{array}{l} v \in \mathscr{V}, \quad i \in \mathscr{N}_v, \\ t - T^{OP}_{vit} \in \mathscr{T}^{TW}_i \wedge t \in \mathscr{T}^E | t > T^{OP}_{vit} \end{array} \tag{5}$$

$$\sum_{(j,i) \in \mathscr{A}_v} x_{vji(t - T^{SP}_{vjit})} + w_{vi(t-1)} = y_{vit} + w_{vit} \qquad \begin{array}{l} v \in \mathscr{V}, \quad i \in \mathscr{N}_v, \\ t \in \mathscr{T}^{TW}_i \quad \wedge t \in \mathscr{T} | t > T^{SP}_{vijt} \end{array} \tag{6}$$

$$\sum_{j \in \mathscr{N}_v} \sum_{t = T^B_v}^{T} x_{vo(v)jt} = 1 \quad v \in \mathscr{V} \tag{7}$$

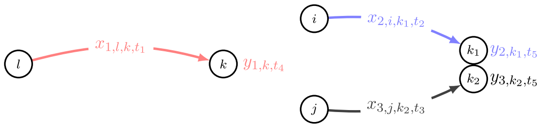
$$\sum_{i \in \mathscr{N}_v} \sum_{t \in \mathscr{T}^E} x_{vid(v)t} = 1 \quad v \in \mathscr{V} \tag{8}$$

$$\sum_{v \in \mathscr{V}_i} \sum_{\tau=0}^{t - T^O_{vi\tau}} y_{vi\tau} + \sum_{k \in \mathscr{K} | i \in \mathscr{N}^C_k} \sum_{v \in \mathscr{V}_k} \sum_{\tau=0}^{t - T^O_{vk\tau}} y_{vk\tau} \geqslant \sum_{v \in \mathscr{V}_j} y_{vjt} \quad i,j \in \mathscr{N} | P_{ij} = 1, \;\; t \in \mathscr{T}^{TW}_j \tag{9}$$

$$\sum_{v \in \mathscr{V}_i} y_{vit} - \sum_{v \in \mathscr{V}_j} y_{vjt} = 0 \qquad i,j \in \mathscr{N} | S_{ij} = 1, \quad t \in \mathscr{T}^{TW}_i \cap \mathscr{T}^{TW}_j \tag{10}$$

$$x_{vijt} \in \{0,1\} \qquad v \in \mathscr{V}, (i,j) \in \mathscr{A}_v, \quad t \in \mathscr{T} \tag{11}$$

$$y_{vit} \in \{0,1\} \qquad v \in \mathscr{V}, \quad i \in \mathscr{N}_v, \quad t \in \mathscr{T}^{TW}_i \tag{12}$$



(a) One vessel **(b)** Two vessels

Fig. 3. Let task l denote the previous task of vessel 1, and task i and task j denote the previous tasks of vessels 2 and 3, respectively. Let task k denote a consolidated task which in this example can be performed by vessel 1 alone, visualized in **(a)**. Alternatively, the two subtasks k_1 and k_2 that constitute k can be performed by vessels 2 and 3 simultaneously, visualized in **(b)**.

$$w_{vit} \in \{0,1\} \quad v \in \mathscr{V}, \quad i \in \mathscr{N}_v, \quad t \in \mathscr{T} \tag{13}$$

$$z_i \in \{0,1\} \qquad i \in \mathscr{N} \tag{14}$$

The objective function (1) maximizes the total profit obtained by servicing the tasks minus the sailing costs. Constraints (2) ensure that each vessel cannot do more than one activity at the same time. Some sailing legs are exempt from these constraints. These are the sailings with a duration of zero time increments, which indicate that a vessel is sailing between two tasks at the same location or is sailing to its dummy end task. In these situations, the vessel can do the sailing and start the task or wait in the same time period, as illustrated in Fig. 2. Constraints (3) ensure that each single task is started at most once within its time window. Constraints (4) do the same for the consolidated tasks. Here, either the consolidated task k itself or its subtasks in the set $\mathscr{N}_k^C$ are to be conducted. Fig. 3 illustrates these two options, where Fig. 3(a) shows the processing of the consolidated task k itself while Fig. 3(b) shows the processing of such a task through two ships that serve one of the substasks from set $\mathscr{N}_k^C$ each. Note that the subtasks are linked through simultaneous requirements that are handled in Constraints (10) such that either both of them are performed in parallel or none of them is performed. Constraints (5) ensure that after a vessel has completed a task, the vessel must sail from that task to its next one. They also ensure that a vessel is allowed to sail to the dummy end node after the end of the planning horizon if the duration of the last task is longer than the remainder of the planning horizon. Constraints (6) ensure that a sailing leg is either followed by starting the task or waiting. Likewise, waiting is either followed by starting the task or another time period of waiting. It can be noted that Constraints (5) and (6) also reduce symmetry in the problem by ensuring that waiting is always done before a task is serviced. Constraints (7) force each vessel to sail from the start task exactly once, while Constraints (8) ensure that each vessel must sail to the dummy end task exactly once. Constraints (9) ensure that task i is completed before task j if there is a precedence requirement between the two tasks, including the consideration that i may be a subtask of a complex task k. Constraints (10) ensure that two tasks are started at the same time if there is a synchronization requirement for the two tasks. Constraints (11), (12), (13) and (14) are binary constraints for the variables.

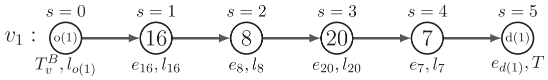


Fig. 4. Solution representation for vessel v_1. The task numbers i are contained within the circles, while s represents the task's position in the route. $o(1)$ indicates the start task for v_1 and $d(1)$ indicates the dummy end task. Using $i(s)$ to refer to a task, we see from the example that $i(2) = 8$. Each task is associated with an earliest, e_i, and latest, l_i, starting time. Here, T is the final period in $\mathscr{T}^E$.

3. Adaptive large neighborhood search heuristic

This section presents the ALNS heuristic for the ASVRP. The ALNS heuristic, which was originally introduced by Ropke and Pisinger (2007) for the pickup and delivery problem with time windows, explores neighborhoods through the use of a series of destroy and repair operators according to an adaptive process. Liu et al. (2019) show how the original ALNS heuristic can be adapted to the VRP with synchronization constraints by introducing a 'sequence vector' to record the order of synchronized customers and a special destroy heuristic. Our ALNS heuristic is based on the ALNS heuristics by Ropke and Pisinger (2006) and Liu et al. (2019), but includes additional functionality in order to tackle the problem specific aspects of the ASVRP.

Section 3.1 gives an overview of the ALNS heuristic and shows how a solution is represented. Section 3.2 gives a description of the construction heuristic used to obtain an initial solution, while Section 3.3 shows how the ALNS heuristic handles interdependencies between routes. Section 3.4 presents the destroy and repair heuristics.

3.1. Solution representation

A feasible solution to the ASVRP, x, has an objective function value $f(x)$. Each solution consists of a set of vessel routes $\mathscr{V}$ and a set of unrouted (not serviced) tasks $\mathscr{U}$. Each vessel route $v \in \mathscr{V}$ is described by a route consisting of a start task $o(v)$, the dummy end task $d(v)$ and its assigned tasks, in the order they are to be performed. Each task in a vessel route has a task number i and a number s which represents the task's position in the route. We refer to a task in a certain position s in a given route as $i(s)$. Furthermore, we keep track of the earliest and latest possible starting times of each task along each route. Fig. 4 illustrates the solution representation with an example vessel route.

3.2. Constructing the initial solution

The construction heuristic is an insertion heuristic and is described in Algorithm 1. A route is created for each vessel, each initialized with the vessel's start task, $o(v)$, and dummy end task, $d(v)$. The tasks are sorted based on importance, represented by the benefit B_{it}^T gained by starting the task in the first time period of its time window, before the heuristic attempts to insert them sequentially into a vessel route by iterating through each vessel route and each position in that route. The feasible insertion with the largest positive profit increase for the task currently evaluated is chosen. If no feasible profit-increasing insertion is found, the task is added to a set of unrouted tasks, $\mathscr{U}$.

Algorithm 1: Construction Heuristic

```
$sortedTasks$ = list of all tasks, sorted in descending order according to the benefit gained by performing each task as early as possible
$\mathcal{V}$ = set of vessels; contains one route for each vessel, initially the routes only contain the start task and dummy end task
$\mathcal{U}$ = set of unrouted tasks, initially the set is empty
$\mathcal{P}_v$ = set containing information about the precedence tasks in route $v \in \mathcal{V}$, initially the set is empty
$\mathcal{S}_v$ = set containing information about the simultaneous tasks in route $v \in \mathcal{V}$,
  initially the set is empty
for each task $i$ in sortedTasks list do
    highest profit increase = 0
    Reset $BestInsertion$
    for vessel $v \in \mathcal{V}$ do
        for position $s$ in vessel route $v$ do
            Calculate $e_i$, $l_i$
            if $Feasible(s, i, \mathcal{P}_v, \mathcal{S}_v)$ and $\Delta Profit(s, i) >$ highest profit increase then
                Update highest profit increase
                $BestInsertion = (v, s)$
            end
        end
    end
    if highest profit increase>0 then
        Insert $i$ into $BestInsertion$
        Update $v$
        Update other routes in $\mathcal{V}$ according to $\mathcal{S}_v$ and $\mathcal{P}_v$ to ensure the
          synchronization constraints
    else
        Add $i$ to $\mathcal{U}$
    end
end
```

3.2.1. *Inserting tasks*

The earliest and latest starting times of $i(s)$ is calculated based on the earliest and latest starting times of the tasks in positions before, $s-1$, and after the insertion, $s+1$, as well as the task's time windows. Eqs. (15) and (16) show how the starting times of task $i(s)$ are calculated. $T^S_{v,i(s-1),i(s),(e_{i(s-1)}+T^O_{v,i(s-1),e_{i(s-1)}})}$ denotes the sailing time from task $i(s-1)$ to task $i(s)$. $T^O_{v,i(s-1),e_{i(s-1)}}$ denotes the time it takes to perform task $i(s-1)$. Similarly, $T^S_{v,i(s),i(s+1),(e_{i(s)}+T^O_{v,i(s),e_{i(s)}})}$ denotes the sailing time from task $i(s)$ to the next task, $i(s+1)$. $T^O_{v,i(s),e_{i(s)}}$ denotes the time it takes to perform task $i(s)$. The earliest starting time of $i(s)$ is computed according to Eq. (15).

$$e_{i(s)} = max\{E_{i(s)}, e_{i(s-1)} + T^O_{v,i(s-1),e_{i(s-1)}} + T^S_{v,i(s-1),i(s),(e_{i(s-1)}+T^O_{v,i(s-1),e_{i(s-1)}})}\} \qquad (15)$$

Since the durations of the sailing and service times are time dependent, we base the calculations of the earliest starting time for task $i(s)$ on the previous task starting in its earliest starting time. This is based on the fact that no later starting time will result in the vessel being able to finish a task or a sailing earlier than starting in the earliest starting time. Thus, we ensure the earliest possible finish time by this choice.

$$l_{i(s)} = min\{L_{i(s)}, l_{i(s+1)} - T^S_{v,i(s),i(s+1),(e_{i(s)}+T^O_{v,i(s),e_{i(s)}})} - T^O_{v,i(s),e_{i(s)}}\} \qquad (16)$$

The latest starting time of $i(s)$ is calculated in Eq. (16) based on the latest starting time of $i(s+1)$. However, due to the time dependency, the latest starting time is dependent on itself in order to determine the correct duration of servicing task $i(s)$ and the correct sailing time from $i(s)$ to $i(s+1)$. As these are not yet possible to assign, we use the duration as if the task were to be performed in its earliest starting time, and sailing for $i(s+1)$ directly after. In the case where the weather conditions get worse and the durations increase in the period between the earliest and latest starting time of task $i(s)$, this approximation could lead to the latest starting time being set too late. Then, starting task $i(s)$ in its latest starting time and sailing for task $i(s+1)$ directly after, would lead to a later arrival than the latest starting time for task $i(s+1)$. Therefore, the latest starting time is recalculated recursively with the latest starting time found, until it is feasible to start performing task $i(s)$ in its latest starting time and arrive at task $i(s+1)$ before its latest starting time.

Fig. 5 shows an example of calculating the earliest and latest starting times for a route for vessel 1 with the task sequence 5, 6 and 7. The solid line path indicates starting each task in the earliest starting time, and the dashed line path indicates starting the tasks in the latest. Starting the tasks in any time period between the earliest and latest starting time would also be feasible. In Fig. 5, task 6 is not bound by a time window as $E_6 = 1$ and $L_6 = 15$, which is the first and last time period in the planning horizon. The filled nodes indicate the vessel's service times for the tasks. Note that task 5 can be completed in three time periods when started in $t = 2$, but takes four time periods to complete when started in $t = 6$.

To check the feasibility of inserting task i in position s, we use the earliest and latest starting times, $e_{i(s)}$ and $l_{i(s)}$, respectively. If the sum of the sailing time from $i(s-1)$ to $i(s)$, the service time of $i(s)$ and the sailing time from $i(s)$ to $i(s+1)$ is greater than the difference between $e_{i(s-1)}$ and $e_{i(s+1)}$, the earliest starting time $e_{i(s)}$ will be greater than the latest starting time $l_{i(s)}$, which means that the insertion is infeasible.

Inserting precedence tasks

If a task i holds precedence over another task j, task i is placed before j in the sorted list. Upon inserting task j, we first check if i is inserted in $\mathcal{U}$. If so, j is also added to $\mathcal{U}$. On the other hand, if i is assigned to a route, we try to find a feasible insertion for j that respects the precedence constraint. Its earliest starting time is then set according to Eq. (17), i.e. the maximum of the time found by Eq. (15) for task j and the earliest starting time of task i plus the service time of i. Note that there exists no

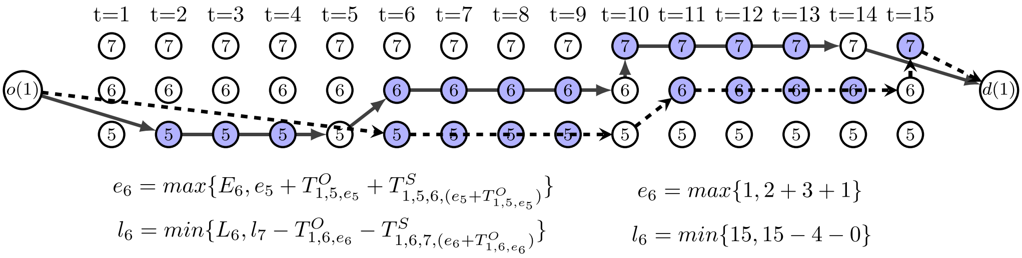


Fig. 5. Example of how the earliest and latest starting times are calculated. The solid and dashed paths indicate starting the tasks in their earliest and latest starting times, respectively. The tasks completed in this scenario are 5, 6 and 7, while $o(1)$ and $d(1)$ are the start and dummy end task of vessel 1, respectively.

restriction on the completion of task j within the planning horizon. Task i can thus be performed even if j cannot be inserted in a solution.

$$e_j = max\{e_j, e_i + T^O_{vite_i}\} \tag{17}$$

Inserting simultaneous tasks

If a task i must be performed simultaneously with task j, the insertion of the first task, i, follows the described procedure and its earliest and latest starting times are set according to Eqs. (15) and (16). After task i is inserted, the next task to be inserted is task j. Upon inserting task j, we first check if i has been assigned to the set of unrouted tasks, $\mathscr{U}$, if so, j is also added to $\mathscr{U}$. Otherwise, the earliest and latest starting times of j are found according to Eqs. (15) and (16). Furthermore, we require the starting times of i and j to be equal, hence we further restrict $e_j = max\{e_j, e_i\}$ and $l_j = min\{l_j, l_i\}$. Then, we update e_i and l_i in the same way, to ensure that $e_i = e_j$ and $l_i = l_j$. If there does not exist a feasible insertion of task j into a vessel route, the completion of task i is also not feasible, and the task is removed from its assigned vessel and added to $\mathscr{U}$.

Inserting consolidated tasks

For consolidated tasks, either the consolidated task k or its subtasks in set $\mathscr{N}^C_k$ can be assigned to vessel routes. To make the insertion as simple as possible in the construction heuristic, we first try to assign the consolidated task k. If we cannot find any feasible profit increasing insertion for k, we try to insert the subtasks instead. Note that all subtasks belonging to a same consolidate task are linked through mutual simultaneous requirements. Therefore, if we do not find feasible insertions for all the subtasks, then they are added to $\mathscr{U}$.

3.2.2. Updating the route

When inserting task i into a route v, the earliest starting times of the tasks following i in the route, and the latest starting times for the tasks placed before i in the route can be affected. If the insertion of a new task $i(s_1)$ requires the starting times of the other tasks to be updated, then the earliest starting time of the tasks in positions $s_2 \in [s_1+1, d(v)]$ are updated according to Eq. (18), and the latest starting times of the tasks in position s_3 for $s_3 \in [s_1-1, 0)$ are updated according to Eq. (19). In the equations, the time index $t_1 = e_{i(s_2-1)} + T^O_{v,i(s_2-1),e_{i(s_2-1)}}$ is the earliest finish of the previous task and the time index $t_2 = e_{i(s_3)} + T^O_{v,i(s_3),e_{i(s_3)}}$ is the earliest finish of the current task.

$$e_{i(s_2)} = max\{e_{i(s_2)}, t_1 + T^S_{v,i(s_2-1),i(s_2),t_1}\} \tag{18}$$

$$l_{i(s_3)} = min\{l_{i(s_3)}, l_{i(s_3+1)} - T^S_{v,i(s_3),i(s_3+1),t_2} - T^O_{v,i(s_3),e_{i(s_3)}}\} \tag{19}$$

If the earliest starting time or the latest starting time does not change for a task, the process of updating is stopped. This occurs when a time window or the synchronization constraints of a task restrict the propagation of changes.

3.2.3. Calculating the change in profit

To find the best insertion for a task, we calculate the profit change for each feasible insertion. The profit change for a given insertion is calculated as shown in Eq. (20) and is defined as the additional benefit of inserting a task minus the extra sailing cost and the reduced completion of other tasks (in the case where inserting a task in a route leads to a smaller part of other tasks being performed within the planning horizon). After calculating the change in profit for all feasible insertions, we choose the insertion with the largest positive profit change. Insertions with negative profit changes are not accepted.

$$\begin{aligned}\Delta Profit\ (i(s)) = \ & B^T_{i(s),e_{i(s)}} - (C^S_{v,i(s-1),i(s),t_1} + C^S_{v,i(s),i(s+1),t_2} - C^S_{v,i(s-1),i(s+1),t_1}) \\ & + B^T_{i(n),e^{New}_{i(n)}} - B^T_{i(n),e^{Old}_{i(n)}}\end{aligned} \tag{20}$$

$B^T_{i(s),e_{i(s)}}$ denotes the profit of performing task $i(s)$ starting in time period $e_{i(s)}$, where $i(s)$ is the task we try to insert in position s. $C^S_{v,i(s-1),i(s),t_1} + C^S_{v,i(s),i(s+1),t_2} - C^S_{v,i(s-1),i(s+1),t_1}$ denotes the change in sailing cost, subtracting the sailing costs from $i(s-1)$ to $i(s)$ and $i(s)$ to $i(s+1)$, and adding the sailing cost from $i(s-1)$ to $i(s+1)$ which distance will no longer be sailed. Sailing leg starting times, t_1 and t_2, are set as $t_1 = e_{i(s-1)} + T^O_{v,i(s-1),e_{i(s-1)}}$ and $t_2 = e_{i(s)} + T^O_{v,i(s),e_{i(s)}}$, respectively. Further, $B^T_{i(n),e^{Old}_{i(n)}}$ denotes the profit of starting the last task in the route, $i(n)$, at its current earliest starting time, while $B^T_{i(n),e^{New}_{i(n)}}$ denotes the profit of starting the last task in its new earliest starting time, given the new insertion.

To increase the probability of finding a feasible insertion for a precedence task, where i holds precedence over j, earlier placements of i are incentivized by adding the term $(T - e_i) \cdot \rho$ to the profit change, where T is the length of the planning horizon and ρ is a constant.

3.3. Handling interdependencies

When changing a route where one or more tasks are bound by synchronization constraints, additional feasibility checks and updates can be required. This may lead to chains of starting times needing to be updated, affecting multiple vessel routes. In the following we present the effects caused by inserting tasks in a route containing further tasks bound by synchronization constraints, and how we avoid cross synchronization.

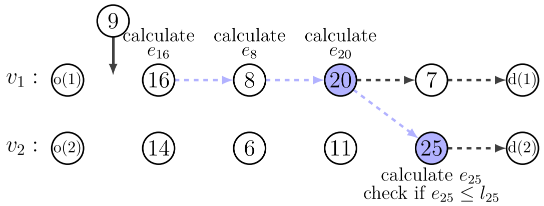


Fig. 6. Case 1: Feasibility check and updates in the case where we insert a task earlier in the route than a task that holds precedence over another task in another route. Task 20 holds precedence over task 25.

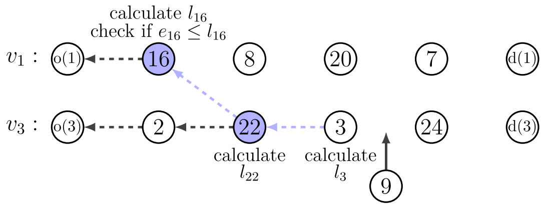


Fig. 7. Case 2: Feasibility check and updates for the case where we insert a task later in the route than a task that a task in another route holds precedence over. Task 16 holds precedence over task 22.

3.3.1. Feasibility checks and updates after insertion

When inserting a task into a route, we distinguish between three cases which require interconnected routes to be updated. Case 1 refers to the situation when a task is inserted into a route where there exists a task later in the route that holds precedence over a task in another route. Case 2 occurs when we insert a task into a route where there exists a task earlier in the route, that a task in another route holds precedence over. Case 3 occurs when we insert a task into a route where there exists a simultaneous task. Cases 1 and 2 are exemplified in Figs. 6 and 7. In these examples, the dashed lines indicate the chains of calculations that may need to be computed in order to check the feasibility of an insertion. If we end up performing the evaluated insertion, we update the earliest starting times of the affected tasks, for as long as the changes are propagating.

In the example of Case 1 in Fig. 6, task 20 holds precedence over task 25. We are evaluating the insertion of task 9 earlier in the route than task 20, and therefore the earliest starting time of task 20 may be affected. Task 20 needs to be completed before task 25 is started. Therefore, if e_{20} changes, we need to check if e_{25} must be changed. If e_{25} changes, we need to check if $e_{25} \leqslant l_{25}$ is still satisfied. If not, the insertion is infeasible.

In the example of Case 2 in Fig. 7, task 16 holds precedence over task 22. We are evaluating the insertion of task 9 later in the route than task 22, and therefore the latest starting time of task 22 may be affected. Task 22 needs to be started after task 16 is finished. Therefore, if l_{22} changes, we need to check if l_{16} must be changed. If l_{16} changes, we need to check if $e_{16} \leqslant l_{16}$ is still satisfied. If not, the insertion is infeasible.

In Case 3, when inserting a task into a route with a simultaneous task, it does not matter if the insertion position is before or after the simultaneous task, as the simultaneous task needs to have both equal earliest and latest starting times as its connected task. Hence, if the insertion position is before or after the position of the simultaneous task, the feasibility checks and updates are similar to the examples in Figs. 6 and 7 for precedence tasks, respectively.

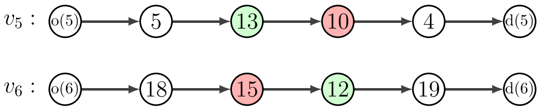


Fig. 8. Example of cross synchronization for simultaneous operations. Task 10 is simultaneous with task 15 and task 13 is simultaneous with task 12. Since task 13 appears before task 10 in the first route and task 15 appears before task 12 in the second route, simultaneous processing of 12 and 13 as well as of 10 and 15 cannot be established. Thus, the shown routes are infeasible.

3.3.2. Checking for cross synchronization

When inserting tasks bound by precedence or simultaneous constraints, a problem referred to as cross synchronization might arise. The problem, exemplified in Fig. 8, is discussed in detail by Liu et al. (2019). We choose a slightly different approach to avoid cross synchronization. To avoid cross synchronization we check if there already are simultaneous tasks in the route. If so, we make sure that the pairs of simultaneous tasks are placed in the correct order.

For the example in Fig. 8, assume that we want to insert task 12 in the shown position in the route of vessel 6. Here, we find that task 15 is a simultaneous task in the route for vessel 6. Then, we check if the task that needs to be performed simultaneously with task 15, i.e., task 10, is placed in the same route as the task that needs to be performed simultaneously with task 12, i.e., task 13. If so, we make sure that the two pairs of simultaneous tasks are placed in the same order, meaning that both tasks 10 and 15 must be performed before tasks 13 and 12, or vice versa. Similar checks are also done for precedence tasks.

3.4. Large neighborhood search

In each iteration of the ALNS, one destroy and one repair heuristic are selected from a set of destroy and repair heuristics, respectively. In the following, we describe the destroy and repair heuristics used.

3.4.1. Destroy heuristics

We use the following destroy heuristics; *related removal*, *worst removal*, *worst sailing removal*, *random removal*, *route removal* and *synchronized removal*. Applying any of these heuristics, except for the *synchronized removal*, at least q^{ALNS} percent of all tasks are removed from their current routes, where q^{ALNS} is a parameter given to the heuristic. To maintain the synchronization constraints, the connected task is removed if a simultaneous task is removed from its route or if a task that holds precedence over that task is removed.

The idea behind the related removal is to remove similar tasks from the solution, as similar tasks may be easier to reshuffle while maintaining feasibility. The relatedness of two tasks, r_{ij}, depends on the geographical distance between the tasks, d_{ij}, and the durations of the tasks, $T^O_{v_1,i,e_i}$ and $T^O_{v_2,j,e_j}$, according to Eq. (21). The smaller r_{ij}, the more related are tasks i and j. a_0 and a_1 are weight parameters.

$$r_{ij} = a_0 d_{ij} + a_1 |T^{O}_{v_1,i,e_i} - T^{O}_{v_2,j,e_j}| \tag{21}$$

While the worst removal sorts the routed tasks in increasing order based on how much they contribute to the profit, calculated according to Eq. (20), the new worst sailing removal only considers the sailing cost part of Eq. (20). The worst sailing removal is thus a customization of the worst removal method. Similarly to the worst removal method, it removes the task having the smallest contribution to the objective function until q^{ALNS} tasks are removed. However, as the contribution to the objective function for each task is calculated using only the sailing cost but not the profit, the method removes tasks whose positions cause excessively long sailings in a solution, rather than tasks that are placed at the end of a route or tasks with low profit. The corresponding contribution for all tasks is calculated before removing any tasks. Similar to Ropke and Pisinger (2006), we use a determinism parameter p for the related removal, worst removal and worst sailing removal heuristics. This approach can flexibly adapt the selection of tasks from a deterministic mechanism to a probabilistic selection process. Details of the parametrization of p are provided in Appendix A.

The random removal randomly chooses a task to remove from all tasks, until at least q^{ALNS} percent of the tasks are removed. The route removal randomly chooses a vessel route and removes all tasks in the route. If the share of the removed tasks is less than q^{ALNS}, the same procedure is repeated for another route. The synchronized removal, inspired by Liu et al. (2019), is specially designed for handling the synchronization constraints by removing all simultaneous and precedence tasks. After all removals are performed, the sets $\mathscr{P}_v$ and $\mathscr{S}_v$ are emptied.

3.4.2. *Repair heuristics*

We have implemented two repair heuristics; *best insertion* and *regret–k insertion*. Both methods are adapted from the repair heuristics presented by Ropke and Pisinger (2006). Each time we apply a repair heuristic, all unrouted tasks are evaluated for insertion, i.e. both the tasks that are removed by a destroy heuristic and the tasks that were already in $\mathscr{U}$ before the destroy heuristic was applied.

The best insertion heuristic uses the construction heuristic described in Section 3.2, but with a different sorting procedure of the tasks. In the construction heuristic the tasks are sorted once and for all, while in the best insertion method, the change in the objective function is calculated for all tasks for all feasible insertions in each iteration. The task giving the largest increase in the objective function when inserted at its best position is then chosen according to Eq. (22).

$$\text{argmax}_{i\in\mathscr{U},v\in\mathscr{V}} \Delta \mathit{Profit}\ (i(s)) \tag{22}$$

$\Delta \mathit{Profit}\ (i(s))$ is calculated as stated in Eq. (20). $\Delta \mathit{Profit}\ (i(s))$ is set to $-\infty$ if there does not exist any feasible insertion for a task. The change in profit for precedence tasks is calculated the same way as in the construction heuristic, described in Section 3.2. For consolidated tasks, we calculate the change in profit for both alternatives, i.e. both for inserting the consolidated task and the two simultaneous tasks that constitute the consolidated task. The best alternative is then compared with the change in profit of the best insertions of other tasks.

For two simultaneous tasks i and j, all feasible insertions for task i are identified first. Each insertion is represented by the change in profit they give. For each feasible insertion of task i, the method attempts to find insertions for task j that satisfies the synchronization constraints. The insertions evaluated are sorted in descending order based on combined profit change for the insertion of both tasks. Upon sorting the tasks to find the best insertion, the combined profit increase for the simultaneous tasks is used to compare the insertion to other single tasks.

The regret–k insertion heuristic compares the k best insertions of a task and calculates the regret value as the sum of the profit difference between the k best insertions. We have used Regret–2 and Regret–3 insertions. For simultaneous tasks, the increase in the objective function for both the best insertion and second best insertion of the pair of tasks, is calculated the same way as described for the best insertion method. The regret value is the difference between these two. For consolidated tasks, the regret value is the difference in the change in profit for the two best insertions, regardless of whether this means inserting the consolidated task or the subtasks that constitute the consolidated task.

Similar to Ropke and Pisinger (2006), a noise term is added to the $\Delta \mathit{Profit}$ value of the insertion alternatives, re-ranking them randomly for the insertion process. The noise parameter η scales the effect of the noise term.

When a repair heuristic has been used to obtain a new solution, a simulated annealing-based acceptance criterion is used to decide whether to accept or reject the solution. We set the temperature T and cooling rate $\varsigma, 0 < \varsigma < 1$ the same way as Liu et al. (2019).

3.4.3. *Choosing a destroy and repair heuristic*

The destroy and repair heuristics are chosen by a roulette wheel selection principle similar to Ropke and Pisinger (2006). To steer the selection process, each destroy and repair heuristic is assigned a weight based on its performance. The weights influence the probability of choosing the heuristics and are updated after each segment of I^S iterations that were conducted by the ALNS. The weight of heuristic d in segment m is given by w_{dm}. We initialize the ALNS with equal weights for all the destroy and repair heuristics. The weights of each the destroy and repair heuristic are updated according to Eq. (23).

$$w_{d,m+1} = (1-r)w_{dm} + r\frac{\pi_d}{\theta_d} \tag{23}$$

The score for heuristic d in the given segment, π_d, is used to calculate the new weights, while θ_d denotes the number of times the heuristic has been selected during the last segment. r is a reaction parameter that determines the responsiveness of the weight updates. If $r = 0$, the weights remain the same as in the last segment, while if $r = 1$, only the scores obtained during the last segment determine the new weights. In the case where $\theta_d = 0$, we set $w_{d,m+1} = w_{dm}$. The weights remain the same for each iteration during a segment. A lower threshold for the weights, κ, is set to 0.2 to ensure that no weights are assigned the value zero. It should be noted that it is only the relative values among the weights for the different operators that matter and not the absolute values. We could therefore have chosen any value above zero as our lower threshold to make sure that an operator always has some probability of being chosen. In each iteration the destroy and repair heuristics used for creating a new candidate solution are chosen by a roulette wheel selection principle, according to Eq. (24), where $\mathscr{J}$ denotes the set of either all destroy or repair heuristics.

$$P(d) = \frac{w_{dm}}{\sum\limits_{\widehat{d}\in\mathscr{J}} w_{\widehat{d}m}} \tag{24}$$

As mentioned, each destroy and repair heuristic, d, receives a score, π_d, within each segment of ALNS iterations. We distinguish between three achievements the destroy and repair heuristics can make; finding a new globally improving solution, finding a new locally improving solution and finding a new solution that is accepted by the acceptance criteria. The destroy and repair heuristics receive rewards, σ_1, σ_2 and σ_3, for each of these three achievements, respectively. Both the destroy and the repair heuristic are rewarded with the same value, as we do not know which of the heuristics that were most important upon creating the candidate solution. The score of one heuristic, π_d, after a segment, is the sum of rewards received in that segment. The scores are reset after each segment. The resulting ALNS is shown in Algorithm 2.

Algorithm 2: Adaptive Large Neighborhood Search for the ASVRP

```
$I^{ALNS}$ = total number of ALNS iterations
$I^S$ = number of iterations in one segment
construct a feasible current solution $x$, set the global best solution $x^* = x$
for $iteration = 1$ to $I^{ALNS}$ do
    Choose a destroy heuristic and a repair heuristic based on adaptive weights $w_{dm}$ for method $d$ in the current segment of iterations $m$
    Generate a candidate solution $x'$ from the current solution $x$ using the chosen destroy and repair heuristics
    if $x'$ is accepted by a simulated annealing–based acceptance criterion then
        set $x = x'$
    end
    Update scores $\pi_d$ of the destroy and repair heuristics
    if $I^S$ iterations has passed since last weight update then
        Update the weight $w_{dm+1}$ for method $d$ for the next segment $m + 1$ based on
          the scores $\pi_d$ obtained for each method in segment $m$
    end
    if $f(x) > f(x^*)$ then
        set $x^* = x$
    end
end
Return $x^*$
```

As a final remark, we want to mention that the developed ALNS omits local search features, which are often used in well-performing ALNS heuristics for vehicle routing, see e.g. Alinaghian and Shokouhi (2018) and Gu et al. (2019). We tested this but observed that it is not helpful for the ASVRP. This is because the combination of time dependent travel and service times, consolidated tasks and precedence and synchronization constraints require that the time-consuming procedures of Section 3.2 have to be called for the feasibility check and evaluation of every local search move. We then observed in preliminary experiments that the ALNS without local search gave significantly better solutions than the ALNS with local search if both were given the same runtime limit. Therefore, we decided not to include local search features in our ALNS heuristic for the ASVRP.

4. Computational study

The computational tests are performed on a PC with 2.10 GHz Intel i7 processor, 8 GB RAM and operating system Windows 10. Java 11 is used to run both the optimization model using the Gurobi 8.1.1 Java interface and the ALNS heuristic. Section 4.1 describes the test instances used for the computational study. Section 4.2 describes the tuning of the parameters used for the ALNS heuristic. In Section 4.3, the performance of the ALNS heuristic is compared to solving the model with Gurobi. Finally, Section 4.4 presents how the ALNS performs with time dependent sailing and service times.

4.1. Test instances

A test instance generator has been developed to create a number of test instances. Partners from the fish farming industry have been involved in this process to ensure that the generated test instances are realistic. A test instance includes a given fleet of service vessels and a set of fish farms with one or more service tasks, and possibly also weather data for the planning horizon. In each test instance, we select a set of service vessels among a set of candidate vessel types with varying characteristics and capabilities. The vessel types are based on a categorization made by SINTEF Ocean (2019) and are presented in Table 1. Each vessel type has a given sailing speed and cost, in addition to a time penalty reflecting that larger vessels require slightly more time for most service operations due to reduced agility.

Furthermore, for each test instance we generate a set of service tasks of different types. Each service task is connected to a fish farm. We use 60 fish farm locations along the middle part of the Norwegian coast from the company MOWI ASA, marked in Fig. 9. The distances between all locations were found by an adapted A*-algorithm, as the shortest paths steering clear of land (Premakumar, 2016). For each of the vessels used in a test instance, its starting position is randomly selected among the locations used in that test instance.

The types of tasks to be performed are shown in Table 2 and represent typical service activities at fish farms. Each task type has a given estimated duration and probability distribution for how frequently it occurs at each fish farm. The tasks are randomly drawn for each test instance based on the occurrence distributions shown in Table 2 for each of the fish farms included in the instance. Each type of task has an importance affecting the profit obtained from performing the task. We have set the profits such that it gives more profit to perform one task of higher importance than two tasks of lower importance.

The capabilities of a vessel determines whether it can perform a given type of task and if it needs assistance of another vessel. The mapping of vessels to tasks is shown in Table 3. The precedence requirements are given in Table 2.

Only tasks of type 10, support for well boat, are limited by time windows in our test instances. These tasks have strict time windows of exactly one time period corresponding to the time the well boat is

Table 1
Candidate vessel types.

Vessel type	Size [m]	Speed [knots]	Sailing cost [USD/hour]	Time penalty
1	<15	10	66	1
2	<15	9	42	1
3	15–24	12	55	1.1
4	15–24	10	56	1.1
5	>24	8	50	1.2
6	> 24	10	55	1.2

Fig. 9. The 60 fish farm locations used in the test instances.

scheduled to start its activities and the supporting service vessel is required to be there.

We use a time discretization of one hour and 60 time periods in the planning horizon in all our test instances. Based on current practice, we assume that the vessels operate between 7 am and 7 pm every day of the week and spend the remaining twelve hours a day moored in proximity to their last task of the day, so that they can pick up where they left off the next morning. This means that the 60 time periods correspond to five days of 12 h each. The test instances generated include 20, 40, 60, 80 and 100 fish farms. We also create test instances with a higher occurrence of task types that are bound by synchronization constraints in order test how this affects the solutions and the performance of the ALNS heuristic. The test instances are labeled with (n) for the normal occurrence, and (h) for high occurrence.

Table 4 presents an overview of the test instances including the number of fish farms, the fleet of service vessels and tasks. The numbers in parentheses of the instances indicate the index of the test instances, e.g. '20-(6–8)-(n)' represents instances 6, 7 and 8 for the case with 20 fish farms and a normal occurrence of tasks bound by synchronized constraints. The column 'avg. S/C/P' refers to the number of simultaneous tasks, consolidated tasks and precedence tasks, respectively. In Table 4, the first three lines represent the 15 test instances used in the parameter tuning (Section 4.2), while the remaining ones represent the 30 instances used when testing the performance of the ALNS heuristic (Section 4.3). The instances are available at http://www.scm.bwl.uni-kiel.de/de/forschung/research-data.

Table 3
Mapping of task types and the vessels that can perform them. Some tasks may require a single vessel or two vessels operating simultaneously to be completed.

Operation type	Single vessel [vessel nr.]	Multiple vessel	
		[Task 1 – vessel nr.]	[Task 2 – vessel nr.]
1,3,8,10,14	2, 3, 4, 6		
2,9		2, 3, 4, 6	2, 3, 4, 6
4		5	2, 3, 4, 6
5	6	2, 3, 4	2, 3, 4
6,13	2		
7	4, 6		
12	1, 3		
11	1, 2, 3, 4, 6		

4.2. Parameter tuning and operator performance

The parameters used for the ALNS heuristic were introduced in Section 3. Each of the tested parameter values were run on each of the 15 parameter tuning instances five times for 25,000 iterations. The initial values of the tuned parameters and the final values of the parameters that are not tuned are inspired by the results of Ropke and Pisinger (2006) and Liu et al. (2019), and adapted through systematic testing while developing the heuristic to scale the values for the ASVRP.

For each parameter, three to five different values were tested. The most appropriate values were selected based on a trade-off between run time and solution quality. Only one parameter was changed at a time. When moving to the tuning of the next parameter, the final values of the already tuned parameters and the initial values of the not already tuned parameters were used. The tuning process was performed once for each parameter. The process of tuning the parameter values of the ALNS is described in more detail in Appendix A, which also includes Table 11 summarizing the initial and final values from the testing.

We have also done tests to assess the performance and contribution of the different destroy and repair operators of the ALNS heuristic. The results of these tests are summarized in Appendix B and show that all operators contribute to the heuristic's performance.

4.3. Computational results

Table 5 summarizes the tests comparing the performance of the ALNS heuristic to Gurobi on the test instances with 20, 40 and 60 fish farms. The results obtained by Gurobi after a maximum run time 3600 s are shown together with the results of the ALNS heuristic. We ran the

Table 2
Task types represented with description, mean and standard deviation of the occurrence interval for each fish farm, duration and importance measure. The occurrence interval follows a normal distribution. Some tasks have (–) as occurrence interval, as another task holds precedence over these tasks. They are thus automatically added if the task that holds precedence is drawn from the distribution.

Task #	Description	Occurrence Interval		Duration [hours]	Importance	Precedes
		Mean [hours]	σ [hours]			
1	Delivery of net	17,520	730	8	2	2,3
2	Installation of net	–	–	4	2	3
3	Return of net	–	–	8	2	
4	Delousing	1152	192	5	1	
5	Larger inspection	8760	360	20	3	
6	Washing of net	5110	730	5	2	
7	Tensioning of mooring	8760	360	48	3	
8	Smaller transportation	8760	360	6	2	9
9	Smaller installations	–	–	3	2	
10	Support for well boat	750	100	4	1	
11	Inspection by ROV	750	100	5	2	
12	Inspection by diver	8760	360	4	2	
13	Washing of pen	8760	360	4	3	
14	Support for working boat	168	24	3	2	

Table 4
The test instances used for the computational study and their associated properties.

Instance	Fish farms #	Vessels	Number of Tasks			
			min.	max.	Avg.	Avg. S/C/P
20-(1–5)-(n)	20	3,4,5	17	29	23.6	4.0/0.0/0.6
40-(1–5)-(n)	40	2,3,4,5,6	43	51	46.4	7.2/0.2/4.0
60-(1–5)-(n)	60	1,2,3,3,4,4,5,6	66	78	71.8	8.8/0.4/3.4
20-(6–8)-(n)	20	3,4,5	17	22	20.0	0.7/0.0/0.0
20-(6–8)-(h)	20	3,4,5	23	35	29.0	5.3/0.7/2.7
40-(6–8)-(n)	40	2,3,4,5,6	47	51	48.7	2.7/1.0/1.0
40-(6–8)-(h)	40	2,3,4,5,6	50	60	55.3	8.7/0.7/7.7
60-(6–8)-(n)	60	1,2,3,3,4,4,5,6	62	70	65.7	7.3/0.7/4.3
60-(6–8)-(h)	60	1,2,3,3,4,4,5,6	68	81	74.3	18.0/0.7/11.7
80-(6–8)-(n)	80	1,2,2,3,3,4,4,5,5,6,6	81	96	88.7	9.3/0.0/1.3
80-(6–8)-(h)	80	1,2,2,3,3,4,4,5,5,6,6	74	101	88	11.3/1.7/7.3
100-(6–8)-(n)	100	1,2,2,3,3,3,4,4,4,5,5,6,6	101	117	108.3	12.7/0.7/3.3
100-(6–8)-(h)	100	1,2,2,3,3,3,4,4,4,5,5,6,6	118	129	122	19.3/1.7/9.7

ALNS heuristic for each of the test instances ten times. In the table, the column ‘Avg. Obj.’ presents the average objective value. The columns ‘Avg. Gap’, ‘Max. Gap’ and ‘Min Gap’ show the average, maximum and minimum gaps between the objective values and the best solutions produced in the experiment, either obtained by Gurobi or the ALNS. The columns, ‘Avg. Gap BB’ and ‘Min. Gap BB’ present the average and minimum percentage difference between the ALNS objective and the best (upper) bound produced by Gurobi. The column ‘Avg. Time [s]’ shows the average run times in seconds for each test instance.

For the smallest instances consisting of 20 fish farms, Gurobi is able to find optimal solutions. The average run time for these instances is 845 s for Gurobi (not shown in the table). For the same six instances the ALNS heuristic obtains solutions that are on average 1.07% worse than Gurobi within an average solution time of only 26 s. The gap of 1.07% is mainly due to instance 20–8-(h) with an average gap of 4.6%. The average and maximum gaps are on average highest for the smaller instances with 20 and 40 fish farms. However, since the solution times are so small for these instances, we could solve each instance ten times and obtain the small minimum gaps instead. This also indicates that one can increase the number of iterations and obtain better solutions on these smaller instances.

As the size of the test instances increases, so do the run times and gaps of Gurobi. The average run times of Gurobi are 3151 and 3600 s compared to 172 and 487 s for the ALNS heuristic for the instances with 40 and 60 fish farms, respectively. If we look at the test instances with 60 fish farms, which are also the most realistic ones, it can be noted that the ALNS heuristic obtains significantly better solutions than Gurobi. Comparing the results of the test instances with normal level and high level of synchronized tasks, it does not seem like this affects the results of Gurobi. On the other hand, the ALNS heuristic spends almost twice the amount of time on the high synchronization instances. This is due to the increased number of updates and feasibility checks that must be performed to handle the interdependency among routes. We do however see that the heuristic is able to maintain its average run time below ten minutes, and continues to produce satisfactory gap values compared to the best bounds of Gurobi.

In Table 6, we report the same results for the larger instances with 80 and 100 fish farms. Like in all experiments, we let the ALNS heuristic run for 100,000 iterations when solving these instances. Since Gurobi was not able to produce feasible solutions on most of these instances within 3600 s, we set the time limit for Gurobi to 43,200 s (12 h). However, we want to note that 3600 s (one hour) is considered to be the highest run time acceptable in a practical setting. We see that despite the run time of 12 h, Gurobi has poor solutions with very large gaps on almost all these

Table 5
Comparison between the ALNS heuristic and Gurobi on the instances with 20, 40 and 60 fish farms.

Instance	Gurobi			ALNS					
	Obj.	Gap	Avg. Obj.	Avg. Gap	Max. Gap	Min. Gap	Avg. Gap BB	Min. Gap BB	Avg. Time [s]
20–6-(h)	457 671	0.00 %	453 299	0.96 %	3.13 %	0.00 %	0.96 %	0.00 %	60.6
20–6-(n)	432 869	0.00 %	429 282	0.83 %	2.43 %	0.01 %	0.83 %	0.01 %	14.4
20–7-(h)	442 050	0.00 %	441 984	0.01 %	0.04 %	0.00 %	0.01 %	0.00 %	25.3
20–7-(n)	330 330	0.01 %	330 330	0.00 %	0.00 %	0.00 %	0.01 %	0.01 %	8.0
20–8-(h)	478 073	0.00 %	456 099	4.60 %	4.70 %	4.49 %	4.60 %	4.49 %	37.5
20–8-(n)	424 671	0.01 %	424 666	0.00 %	0.01 %	0.00 %	0.01 %	0.01 %	10.8
Average 20	427 611	0.00 %	422 610	1.07 %	1.72 %	0.75 %	1.07 %	0.75 %	26.0
40–6-(h)	801 180	2.34 %	780 932	2.53 %	4.81 %	1.08 %	4.81 %	3.39 %	246.7
40–6-(n)	814 718	1.48 %	815 541	0.72 %	1.37 %	0.00 %	1.38 %	0.66 %	114.8
40–7-(h)	859 504	0.00 %	848 163	1.32 %	2.75 %	0.54 %	1.32 %	0.54 %	152.6
40–7-(n)	785 760	2.45 %	783 201	0.37 %	1.85 %	0.00 %	2.77 %	2.40 %	107.3
40–8-(h)	809 121	3.79 %	789 581	2.41 %	3.67 %	0.37 %	6.11 %	4.14 %	312.4
40–8-(n)	838 664	2.23 %	831 806	0.82 %	2.39 %	0.01 %	3.03 %	2.23 %	100.0
Average 40	818 158	2.05 %	808 204	1.36 %	2.81 %	0.33 %	3.24 %	2.23 %	172.0
60–6-(h)	312 780	77.31 %	1 287 600	1.59 %	2.90 %	0.00 %	6.61 %	5.10 %	880.6
60–6-(n)	117 525	90.92 %	1 285 444	0.18 %	0.29 %	0.00 %	0.73 %	0.55 %	208.5
60–7-(h)	713 827	49.86 %	1 383 458	1.13 %	2.19 %	0.00 %	2.82 %	1.70 %	574.2
60–7-(n)	1 031 224	4.78 %	1 076 616	0.13 %	0.24 %	0.00 %	0.59 %	0.46 %	289.9
60–8-(h)	771 516	34.72 %	1 176 787	0.13 %	0.30 %	0.00 %	0.44 %	0.30 %	617.1
60–8-(n)	140 853	89.73 %	1 354 474	0.98 %	2.34 %	0.00 %	1.21 %	0.23 %	348.7
Average 60	368 988	57.89 %	1 260 730	0.69 %	1.38 %	0.00 %	2.07 %	1.39 %	487.0

Table 6

Comparison between the ALNS heuristic and Gurobi (with a time limit of 12 h) on the instances with 80 and 100 fish farms.

Instance	Gurobi			ALNS					
	Obj.	Gap	Avg. Obj.	Avg. Gap	Max. Gap	Min. Gap	Avg. Gap BB	Min. Gap BB	Avg. Time [s]
80–6-(h)	1 284 235	1.41 %	1 301 151	0.01 %	0.03 %	0.00 %	0.11 %	0.11 %	1206
80–6-(n)	1 399 305	18.98 %	1 712 541	0.17 %	0.28 %	0.00 %	0.85 %	0.68 %	997
80–7-(h)	1 608 125	13.17 %	1 776 729	1.38 %	2.05 %	0.00 %	4.06 %	2.72 %	1742
80–7-(n)	1 149 398	25.53 %	1 542 068	0.02 %	0.03 %	0.00 %	0.09 %	0.08 %	1952
80–8-(h)	1 092 851	24.44 %	1 440 465	0.20 %	0.43 %	0.00 %	0.40 %	0.20 %	1282
80–8-(n)	1 869 211	3.04 %	1 896 310	0.54 %	1.65 %	0.00 %	1.63 %	1.09 %	2296
Average 80	1 400 521	14.43 %	1 611 544	0.39 %	0.74 %	0.00 %	1.19 %	0.81 %	1579
100–6-(h)	20 434	99.03 %	2 067 093	0.92 %	1.68 %	0.00 %	1.93 %	1.02 %	3682
100–6-(n)	1 442 686	29.07 %	2 026 342	0.15 %	0.38 %	0.00 %	0.37 %	0.22 %	2365
100–7-(h)	1 036 240	55.71 %	2 223 887	0.80 %	2.46 %	0.00 %	4.94 %	4.18 %	2942
100–7-(n)	1 775 888	9.12 %	1 952 354	0.03 %	0.05 %	0.00 %	0.09 %	0.06 %	2033
100–8-(h)	1 447 533	34.74 %	2 145 724	0.60 %	1.09 %	0.00 %	3.27 %	2.69 %	2630
100–8-(n)	1 880 801	16.79 %	2 234 831	0.71 %	1.24 %	0.00 %	1.13 %	0.42 %	2383
Average 100	1 267 264	40.74 %	2 108 372	0.54 %	1.15 %	0.00 %	1.96 %	1.43 %	2673

instances. The ALNS heuristic on the other hand produces very good solutions in significantly less than one hour on average. It can be noted that the average gaps between the solutions provided by the ALNS heuristic and the best (upper) bounds from Gurobi on the instances with 80 and 100 fish farms are merely 1.19 % and 1.96 %, respectively.

In Table 7 we compare the number of tasks not started or serviced, referred to as unrouted tasks, from the results obtained with Gurobi and the ALNS heuristic. The column ‘Tasks’ represents the total number of tasks in the test instance, and the column ‘S/C/P’ shows the number of simultaneous, consolidated and precedence tasks, respectively. Finally, the number of unrouted tasks is presented in the last three columns for Gurobi and the ALNS heuristic, respectively. For the ALNS heuristic, we report both the average and minimum number of unrouted tasks. Looking at these results, we see that Gurobi is able to produce a lower number of not started tasks than the ALNS heuristic for only five of the 30 test instances. On the other hand, on average the ALNS heuristic performs better than or equally good as Gurobi on 23 instances. Furthermore, for the larger test instances, the difference is especially high between Gurobi and the ALNS heuristic with respect to the number of unrouted tasks. For several of these test instances the ALNS heuristic is able to find solutions where all the tasks are started.

Table 7

Comparison of the number of tasks not started between the ALNS heuristic and Gurobi.

Instance	Tasks #	S/C/P #	Unrouted Tasks		
			Gurobi	ALNS Avg.	ALNS Min.
20–6-(h)	35	6/1/8	11	13.3	13
20–6-(n)	22	2/0/0	1	1.0	1
20–7-(h)	23	2/0/0	1	1.0	1
20–7-(n)	17	0/0/0	0	0.0	0
20–8-(h)	29	8/1/0	2	4.3	4
20–8-(n)	21	0/0/0	1	1.0	1
40–6-(h)	56	10/2/7	10	14.1	13
40–6-(n)	51	4/1/0	3	4.7	3
40–7-(h)	50	4/0/4	9	10.2	10
40–7-(n)	48	2/2/3	5	7.2	5
40–8-(h)	60	12/0/12	20	22.0	21
40–8-(n)	47	2/0/0	3	3.2	3
60–6-(h)	81	22/1/4	64	10.0	8
60–6-(n)	65	6/0/0	58	0.3	0
60–7-(h)	74	18/0/11	37	1.9	0
60–7-(n)	62	6/2/6	6	0.9	0
60–8-(h)	68	14/1/10	26	0.0	0
60–8-(n)	70	10/0/7	61	0.5	0
80–6-(h)	74	8/1/6	1	1	1
80–6-(n)	89	12/0/0	17	0	0
80–7-(h)	101	16/0/13	19	7.1	5
80–7-(n)	81	6/0/0	23	1	1
80–8-(h)	89	10/4/3	21	0	0
80–8-(n)	96	10/0/3	3	1.3	1
100–6-(h)	118	16/3/10	112	6.3	1
100–6-(n)	107	14/0/7	30	1	1
100–7-(h)	129	28/1/9	67	14.5	12
100–7-(n)	101	8/1/3	6	0	0
100–8-(h)	119	14/1/10	49	9	7
100–8-(n)	117	16/1/0	21	1.7	0

4.4. *Weather impact*

In the tests in the previous section, the sailing and service times have been time independent, representing a situation with nice and stable weather, typical for the summer. In this section, we analyze how the time dependency affects the ALNS heuristic, the routing of the vessels and the number of tasks performed. We have performed five runs with the ALNS heuristic for each test instance and each of the three weather scenarios referred to as ‘Perfect’, ‘September’ and ‘January’. ‘Perfect’ is the time independent situation with nice and stable weather, while ‘September’ represents a typical weather situation for that month, with mostly nice weather, but with occasional bad weather and large waves. ‘January’ represents typical winter weather, meaning frequently bad weather. The weather data used in the latter two weather scenarios, historical data retrieved from European Centre for Medium-Range Weather Forecasts, is used to approximate realistic weather forecasts. The weather data retrieved is significant wave height for September 1–5, 2019 and January 1–5, 2020 for each hour between 7 am and 7 pm, which are the operating hours. The data is retrieved for coordinates close to the coordinates of the 60 MOWI ASA fish farms shown in Fig. 9. The weather affects sailing speed and operation times for the small vessels of types 1–4 as shown in Table 8. For the larger vessels of types 5 and 6, the upper limit of the first three wave height intervals are increased to 0.5, 1.0 and 1.5 meters, respectively, to reflect the increased seaworthiness of the larger vessels.

The results from this testing are presented in Table 9. The column ‘Gap [BF, BB]’ shows the gaps between the average objective value from the ALNS heuristic and the best found solution (BF) and best bound (BB) with Gurobi within 3600 s, respectively. A positive number for Gap BF

Table 8

Weather effects on sailing speed and service time for vessel types 1–4. WOW = *Waiting On Weather*.

Wave height (meters)	Sailing Speed	Added Service Time
$[0.0, 0.25]$	0	0%
$(0.25, 0.5]$	0	20%
$(0.5, 1.0]$	−2 kn	30%
$(1.0, \infty)$	−3 kn	WOW

Table 9
Results from running the ALNS heuristic with three different weather variants. Gap BF is the gap to the best solution found by Gurobi. Gap BB is the gap to the best bound found by Gurobi. A negative gap means that the value from Gurobi is better.

Instance	Perfect			September			January		
	Gap [BF, BB]	Time[s]	U	Gap [BF,BB]	Time[s]	U	Gap [BF,BB]	Time[s]	U
20–6-(n)	[−0.7%, −0.7%]	21.0	1	[0.0%, −1.0%]	17.0	2	[0.0%, 0.0%]	12.7	11.0
20–7-(n)	[0.0%, 0.0%]	12.4	0	[0.0%, 0.0%]	10.6	0	[0.0%, 0.0%]	11.0	7.0
20–8-(n)	[0.0%, 0.0%]	17.8	1	[−0.5%, −2.2%]	10.6	1.2	[−4.9%, −4.9%]	8.0	12.0
Avg. 20	[−0.2%, −0.2%]	17.1	0.7	[−0.2%, −1.1%]	12.7	1.1	[−1.7%, −1.7%]	10.6	10.0
40–6-(n)	[0.3%, −1.2%]	182.8	3.8	[30.3%, −12.4%]	114.3	7.6	[−5.1%, −15.0%]	28.0	34.0
40–7-(n)	[−0.5%, −3.0%]	168.8	3.8	[48.5%, −16.1%]	53.0	7.2	[−4.1%, −4.1%]	27.0	30.0
40–8-(n)	[−0.9%, −3.2%]	139.0	3.2	[10.7%, −9.8%]	103.0	6.2	[−4.7%, −16.8%]	26.0	32.2
Avg. 40	[−0.4%, −2.5%]	163.5	3.6	[29.8%, −12.8%]	90.1	7.0	[−4.6%, −12.0%]	27.0	32.1
60–6-(n)	[90.9%, −0.7%]	343.2	0.2	[49.8%, −5.1%]	11.4	3.8	[−3.4%, −12.7%]	39.3	43.0
60–7-(n)	[4.2%, −0.6%]	465.8	0.2	[61.8%, −1.5%]	254.0	0.8	[−2.7%, −20.1%]	6.0	38.0
60–8-(n)	[89.6%, −0.9%]	567.8	0	[32.4%, −9.0%]	73.6	7.8	[−5.7%, −20.8%]	3.7	49.0
Avg. 60	[61.6%, −0.7%]	458.9	0.1	[48.0%, −5.2%]	113.0	4.1	[−4.0%, −17.9%]	16.3	43.3
Avg. Tot.	[20.3%, −1.1%]	213.2	1.5	[25.9%, −6.3%]	71.9	4.1	[−3.4%, −10.5%]	18.0	28.5

means that the solution obtained by the ALNS heuristic is better. The column U shows the average number of unrouted tasks.

From the results in Table 9, we observe that the number of unrouted tasks increases as the weather worsens in the 'September' variant, and especially the 'January' variant. Furthermore, the ALNS heuristic uses less time solving the instances with bad and varying weather, than the perfect weather instances. This can be explained by the fact that fewer tasks are routed due to increased sailing and service times, and hence fewer updates need to be performed due to synchronization. From the columns Gap BF and BB, we observe that for the 'September' and 'January' weather variants, the heuristic seems to struggle a bit more with correctly prioritizing the large number of unrouted tasks and the solution quality decreases slightly. However, for the instances and weather variants where Gurobi is far from finding the optimal solution within the time limit of 3600 s, the ALNS heuristic still outperforms Gurobi.

4.5. Economies-of-scale from combined planning of larger geographical regions

Today, the operational planning within the aquaculture industry is made at a regional level. The test instances used until this point, consisting of 20 to 100 fish farms, have all featured locations that are located more or less within the same geographical area, and the ones with sizes from 20 to 60 are comparable to the planning situation faced today. In this section, we have generated test instances consisting solely of the fish farms within separate regions. In the three regions, Trøndelag, Møre og Romsdal, and Vestland, the biggest fish farming company in Norway, MOWI, has 56, 27 and 41 locations, respectively. For each of these regions, we have generated three different test instances and solved them using the ALNS heuristic. To see the potential economies-of-scale from planning for a larger geographical area, the test instances for the three regions have been added together to form a 'super region'. In Table 10, we present the results for each of the three regional instances, and compare the combined solutions from planning each of them individually (the 'SUM' instances) with the solutions from planning the regions as one large (the 'ALNS' instances). We report these results for two different fleets consisting of 13 and 15 vessels of different types, which are both realistic fleet sizes for these three regions combined. For the regional instances, we distributed the initial positions of the vessels among the three regions in a realistic way based on the size and distances within each region.

In the following, we discuss the maximum objective values and minimum number of unrouted tasks, as these numbers tell the most about the potential for economies-of-scale in the planning (these results are obtained from solving each instance by running the ALNS heuristic

Table 10
Comparison of planning for the regions Møre og Romsdal (MR), Trøndelag (TRD), and Vestland (VST) separately, the combined solutions from these (SUM), and together as one super region (ALNS).

Instance	Tasks	13 Vessels					15 Vessels				
		Obj. Value		Time	Unrouted		Obj. Value		Time	Unrouted	
	#	Avg.	Max	[s]	Avg.	Min.	Avg.	Max	[s]	Avg.	Min.
MR-1-(n)	41	503,882	505,549	60.9	15.4	15	712,078	712,797	84.3	0.3	0
MR-2-(n)	25	468,222	468,244	25.8	0.0	0	476,625	476,625	33.3	0.0	0
MR-3-(n)	26	483,466	483,482	22.9	3.0	3	571,625	571,625	26.3	0.0	0
TRD-1-(n)	52	957,857	961,904	182.7	2.4	2	971,621	971,797	164.9	0.3	0
TRD-2-(n)	58	1,051,510	1,057,953	210.0	8.6	8	1153 367	1,154,192	183.3	0.0	0
TRD-3-(n)	42	838,261	838,272	110.6	0.0	0	838,270	838,272	107.8	0.0	0
VST-1-(n)	40	776,022	777,654	80.8	0.0	0	772,811	777,593	82.6	0.1	0
VST-2-(n)	46	789,597	792,331	101.7	4.0	4	789,588	792,331	95.9	4.1	4
VST-3-(n)	50	872,988	879,143	98.7	7.0	7	867,742	879,087	96.3	7.4	6
Super-1-(n) (SUM)	133	2,237,761	2,245,107	324.4	17.8	17	2,456,686	2,462,187	331.8	0.7	0
Super-2-(n) (SUM)	129	2,309,329	2,318,528	337.5	12.6	12	2,419,580	2,423,148	312.5	4.1	4
Super-3-(n) (SUM)	118	2,194,715	2,200,897	232.2	10.0	10	2,277,637	2,288,984	230.4	7.4	6
Super-1-(n) (ALNS)	133	2,223,756	2,259,992	2472.4	19.6	17	2,413,867	2,429,548	2725	6.7	4
Super-2-(n) (ALNS)	129	2,317,721	2,342,513	1996.4	13.3	11	2,445,524	2,454,729	2196.4	3.3	0
Super-3-(n) (ALNS)	118	2,240,560	2,263,012	1644.6	9.4	6	2,377,483	2,386,101	1781.1	0.7	0

ten times). The results in Table 10 show that there might be some potential for economies of scale in the planning. If we disregard the first of the three instances solved with a fleet of 15 vessels, we can see that the maximum objective values for the 'ALNS' instances are between 0.6% and 4.2% better than the 'SUM' instances. This means that we obtain somewhat better solutions when planning the three regions together. This is mainly because we are able to reduce the (minimum) number of unrouted tasks. This is especially true for the third instance solved with a fleet of 15 vessels, with a 4.2% improvement in the (maximum) objective value and a reduced (minimum) number of unrouted tasks from 6 to 0. For the first instance solved with a fleet of 15 vessels, we obtain slightly better results when planning at a regional level. This can be explained by that we are able to find a solution that is closer to optimality for the regional instances than for the combined one.

Even though more analyses are required to conclude, it seems like only relatively small improvements can be achieved on average from planning several regions simultaneously instead of at a regional level. When considering this, it should also be kept in mind that there are significant practical challenges that must be faced when planning several regions combined. In addition to the increased planning complexity due to the increased problem size, there are rules and regulations governing vessels crossing over from one infection control zone to another, e.g., requiring the vessel to be disinfected below the waterline. Such time penalties were not included in this study.

5. Concluding remarks

This paper studied the ASVRP, which is an important planning problem arising in sea-based fish farming. In the ASVRP, there is a set of fish farms located in the sea, where each fish farm has one or more service tasks to be performed by a given heterogeneous fleet of service vessels with different capabilities. Some service tasks have time windows and precedence requirements, and some tasks require simultaneous operation of more than one vessel. Furthermore, varying weather conditions, given by weather forecasts, make the sailing times between the fish farms and the service times of the tasks time dependent. The objective of the ASVRP is to maximize the value of the service tasks performed within a given planning horizon.

We proposed a time discrete optimization model for the ASVRP, formulated as a time dependent, prize collecting vehicle routing problem with synchronization constraints and time windows. Furthermore, we presented an ALNS heuristic for solving the ASVRP. The ALNS significantly extends previous ALNS heuristics to account for the additional complexity of the ASVRP. Each task inserted in a route is represented with both an earliest and a latest starting time, which are used to check the feasibility of insertions with regards to both the intra-route connections and dependencies between routes. Additionally, sets containing information about precedence and simultaneous tasks have been introduced in the ALNS to maintain the synchronization constraints. Inspired from Liu et al. (2019), we have also implemented a new destroy heuristic, called synchronized removal, which removes all tasks bound by synchronization from the solution.

We generated a number of test instances based on real data from the aquaculture industry and it was shown that both the ALNS heuristic and a commercial solver (Gurobi) are able to find high quality solutions in reasonable time for small problem instances with 20 and 40 fish farms. For the medium sized test instances with 60 farms, Gurobi had very high optimality gaps after one hour of running time, while the ALNS heuristic obtained solutions with an average run time of around eight minutes that are on average around only 2% from the best bound obtained by the commercial solver. For the larger test instances with 80 to 100 fish farms, Gurobi was not even able to produce feasible solutions within one hour and still had very high optimality gaps even after 12 h run time. The ALNS heuristic on the other hand produced very good solutions in significantly less than one hour on average with average gaps of less than 2% from the best bound found by Gurobi (after 12 h).

The results summarized above are promising with regards to using the ALNS heuristic as a solver in a future decision support system. The ASVRP is an extremely difficult optimization problem for which there has been no high performance solution method so far. Common industry practice is therefore to manually construct the routes which could lead to a low utilization of the vessels, and hence increased costs. We believe our proposed model and solution method may improve the vessel utilization and reduce costs for the fish farmers.

Even though the performance of the ALNS heuristic is very good, there might still be ways to improve it even further. One such idea is to hybridize the ALNS heuristic by using the promising vessel routes obtained during the ALNS iterations to construct better solutions by solving a set partitioning problem (using Gurobi) once in a while throughout the search.

Declaration of Competing Interest

Acknowledgement

This research has been a part of the research center SFI EXPOSED Aquaculture Operations. We would like to thank SINTEF Ocean and industry partners, including Stian Rakke of Anteo AS, for providing insight into the aquaculture industry. We are also grateful to the two anonymous reviewers, whose comments helped us improve the paper.

Appendix A. ALNS parameter tuning

Table 11 shows the values of the parameters of the ALNS heuristic which were used in the computational study. We used 15 different instances for the parameter setting tests, i.e. five instances each with 20, 40 and 60 fish farms. To find these parameter values, each of the tested parameter values were run on each of 15 parameter tuning instances five times. The initial values of each of the parameters were set equal to the values shown in Table 11, which are values inspired by the results of Ropke and Pisinger (2006) and Liu et al. (2019) though adapted to the ASVRP through an ad hoc trial and error phase. In the following, we briefly describe the process of deciding the parameter values.

The *removal parameter* q^{ALNS} determines the number of tasks that is removed in each iteration of the ALNS heuristic. Inspired by Liu et al. (2019), we use a control parameter $\hat{q}$ and define $q^{ALNS} = \lfloor \hat{q} \times |\mathcal{N}| \rfloor$, where $\hat{q}$ is the percentage of tasks removed in each iteration, and $|\mathcal{N}|$ is the number of tasks. With a small $\hat{q}$ value the algorithm is not able to move far in its search (Ropke and Pisinger, 2006). Meanwhile, including a large $\hat{q}$ value can be time consuming. Similarly as in Liu et al. (2019), five different intervals were tested for $\hat{q}$, namely [5%, 15%], [15%, 30%], [5%, 30%], [15%, 50%] and [30%, 50%]. For each iteration, $\hat{q}$ was selected from a uniform distribution within the given interval. Interval [15%, 50%] performed slightly better than the others and was therefore chosen.

The *weight parameters*, a_0 and a_1, are used for the related removal method. The related removal attempts to find the tasks most similar to a randomly chosen task and remove these from the solution. Here, the weights are used to relate distance and duration, respectively, in order to calculate the relatedness between two tasks. For the test instances used in this paper, the distance and duration measures are highly unbalanced, with durations in

Table 11
Overview of the parameters used in the ALNS heuristic. The parameters that are tuned are presented with an initial value, which was used in the tuning process before the final value was set. The parameters that are not tuned are only presented with a final value.

Parameter	Initial value	Final value	Description
a_0	0.08	0.5	Related removal, distance weight.
a_1	0.5	1.0	Related removal, duration weight.
p	5	5	Determinism parameter.
σ_1	33	33	ALNS score for finding new globally optimal solution.
σ_2	9	9	ALNS score for finding new, locally improving solution.
σ_3	13	9	ALNS score for finding new solution.
r	0.1	0.5	ALNS reaction parameter.
q^{ALNS}	[5%, 30%]	[15%, 50%]	Percentage of tasks to remove. Chosen uniformly at random in the interval.
η	0.250	0.125	Noise control parameter.
κ		0.2	Lower threshold for the adaptive weights.
ρ		20	Precedence control parameter. Benefits placing tasks with precedence early.
ς		$0.2\% \times T_{start}$	Simulated annealing cooling rate.
T_{start}			Simulated annealing start temperature. Set such that the probability of accepting a candidate solution is 50% if the candidate solution is less than 5% worse than the current solution.
I^{ALNS}		25 000	Number of iterations for the ALNS heuristic during the parameter tuning process. In sections using other values of I^{ALNS}, this is specified.
I^S		100	Number of iterations in one ALNS segment.

the interval between three and 58 time periods, and distances in the interval between 0 and 1020 nautical miles. Five different weight settings were used in this tuning process with the values of $a = [0.10, 1.76]$, $[0.01, 4.00]$, $[0.50, 1.00]$, $[0.05, 4.00]$ and $[0.20, 1.00]$, which corresponds to balance the distance and duration, highly favor duration, highly favor distance, slightly favor duration and slightly favor distance, respectively. The results showed the ALNS heuristic is not very sensitive to this setting, but setting [0.20, 1.00] was chosen as it performed slightly better than the others.

The score parameters are used for the adaptive weights adjustment of the ALNS heuristic. As described in Section 3.4.3, σ_1, σ_2 and σ_3 reward finding a new globally improving solution, finding a new, locally improving solution and finding a new solution, respectively. The following five σ vectors were tested: [33,9,1], [9,9,9], [9,9,1], [33,9,9] and [33,9,13]. The results showed that these settings did not have much impact on the solution quality, but setting [33,9,9] was chosen as it performed slightly better than the others on average.

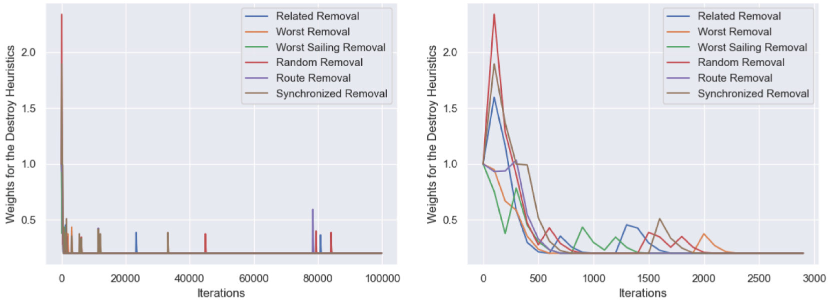
The *reaction parameter r* controls the adaptiveness of the weights after each segment, i.e. I^S iterations, of the heuristic has been run. With $r = 1$ the weights will be updated solely on the scores received in the last I^S iterations, while with $r = 0$ the weights will not be updated. The results showed that letting the weights be solely dependent on the last segment, with $r = 1$, leads to the highest gaps, while keeping r in the interval between 0.10 and 0.50 leads to very similar lower gaps. We chose $r = 0.50$ as this value gave the smallest average gap.

The *noise control parameter* η controls the level of randomness included when deciding which tasks to insert after a removal, where a low value means little randomness is added to the insertion process and vice versa. We tested four different values of the noise parameter, i.e. $\eta = 0, 0.025, 0.125$ and 0.25. The results were very robust also with respect to the value of the noise parameter, but $\eta = 0.125$ was chosen as it performed slightly better on average.

Finally, the determinism parameter p controls the amount of randomness which is included in the worst, worst sailing and related destroy heuristics. Recall that with these heuristics, we decide which tasks to remove from the solution, based on their contribution to the objective function or their relatedness to a selected task. If the value of p equals 1 the removal will be completely random, while the larger p is, the less random the insertion will be. For the tuning of the determinism parameter, the values 3, 5 and 7 were tested. Even though the results did not differ much, we chose $p = 5$ based on the smallest average gap.

Appendix B. Performance of destroy and repair operators

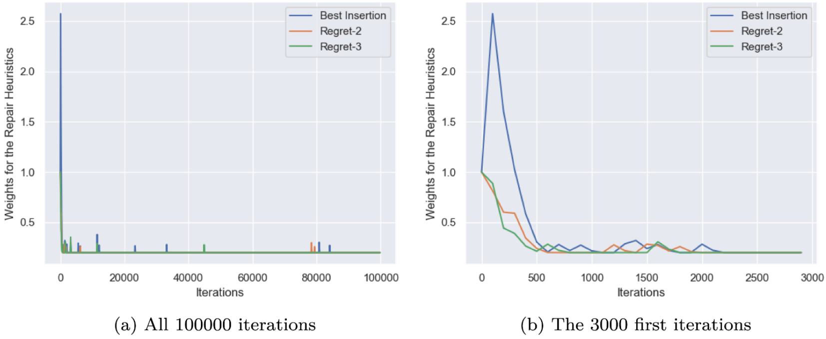
The weights for the destroy and repair operators, and hence their probabilities for being chosen, are adaptive and updated based on their performance for each ALNS segment, as described in Section 3.4.3. Here, we show how the weights develop over the iterations and that all operators contribute to improving the solutions. In Figs. 10 and 11, we observe how the average weights for the destroy and repair heuristics, respectively, of five



(a) All 100000 iterations

(b) The 3000 first iterations

Fig. 10. Weights of the destroy heuristics during a run of the ALNS heuristic. The plots represent the average weights of all five runs of test instance 40-2-(n). Values are sampled at every weight update.



(a) All 100000 iterations (b) The 3000 first iterations

Fig. 11. Weights of the repair heuristics during a run of the ALNS heuristic. The plots represent the average weights of all five runs of test instance 40-2-(n). Values are sampled at every weight update.

different runs on test instance 40-2-(n) evolve throughout the ALNS heuristic. Instance 40-2-(n) is only used as an illustration here as similar patterns were also observed for the other test instances, but we omit these results for the sake of space limitations. The weights are all initialized with a value of 1, and their lower threshold is 0.2.

In Figs. 10(a) and 11(a), we see that the weights have highest values within the first 3000 iterations. This corresponds to that we also see largest improvements in the objective value within the first iterations. After these iterations, we observe that improvements do not happen very frequently, which is shown in that most of these iterations are being performed with the weights at their lower threshold. In Fig. 10(b), we see a clearer picture of how the removal weights behave within the first 3000 iterations. It is difficult to observe a trend, as none of the destroy heuristics seems to perform significantly better than the others. For the weights of the repair heuristics, illustrated in Fig. 11(b), we see that it is the weight for the best insertion heuristic which takes the highest values. However, Ropke and Pisinger (2006) indicate that the ALNS has shown to be relatively robust to the insertion heuristic used and, therefore, the high values for the weight of the best insertion heuristic could be mainly caused by the destroy heuristic it was paired with. Thus, we do not conclude that any of the destroy or repair heuristics are significantly better or worse than the others, but we do however note that they are all used, which also shows that they contribute to improving the solution quality.

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Research paper 3

Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming
Slette, H.T.; Asbjørnslett, B.E.; Pettersen, S.S.; Erikstad, S.O.
Aquacultural Engineering, Vol.97, 2022

Aquacultural Engineering 97 (2022) 102243

Contents lists available at ScienceDirect

Aquacultural Engineering

journal homepage: www.elsevier.com/locate/aque

Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming

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ARTICLE INFO

Keywords:
Emergency response
Fish farming
Biomass hazards
Fish welfare
Discrete event simulation
Response distributions

ABSTRACT

This paper presents a simulation model for analyzing emergency response for fish welfare emergencies in sea-based fish farming. The model enables decision-makers to evaluate the emergency preparedness level against incidents harming fish welfare and the benefit of additional measures such as dedicated emergency response vessels. The proposed model simulates how the vessel operations of a sea-based fish farming system develops over time and tests the emergency preparedness at regular intervals by simulating the emergency responses. The progress of each emergency response is logged and is used to establish first response time, response progression, and response completion duration. A case study is performed assessing the emergency preparedness of two sea-based fish farming systems, and the effects of adding a dedicated emergency response vessel. The results indicate that when there are fewer vessels that can contribute to the emergency response, a dedicated emergency response vessel represents a higher relative capacity increase, and can have a more significant impact on the response completion.

1. Introduction

Sea-based fish farming can be exposed to certain events and conditions that have negative impacts on fish welfare (Sommerset et al., 2020). Some of these hazards can lead to situations necessitating vessel responses such as moving, delousing or slaughtering the fish (Norwegian Food Safety Authority, 2017; Sommerset et al., 2020). In 2016 Chile experienced the most severe harmful algae bloom (HAB) to date, killing 100,000 metric tons of Atlantic salmon (Mardones et al., 2021). In the early summer of 2019 a HAB killed an estimated 8 million farmed salmon along the Norwegian coast, and in 2021 Chile saw another HAB that resulted in the transfer of 5.4 million salmon to safer sites away from the affected area (FishFarmingExpert, 2021; Sommerset et al., 2020). The following winter, sea-based fish farmers on the Faroe Islands lost approximately 1 million fish to winter ulcer at one single occasion (Buanes, 2020). However, the severity of hazards may vary, and locations can experience situations with no serious effects on the fish welfare, such as minor algae blooms. Thus, in this paper the term “emergency” is reserved for serious realizations of the hazards, which will lead to loss of biomass if the emergency response is inadequate.

After the mentioned emergencies in Norway and the Faroe Islands the lack of emergency preparedness was said to contribute to the high losses (Fenstad, 2019; Ilaks.no, 2020; Osnes, 2019; Ytreberg and Berglihn, 2019). Hence analyzing the response preparedness for large scale biomass emergencies in sea-based aquaculture systems could help operators enhance their emergency preparedness and response capabilities. Improvements in emergency management in sea-based aquaculture systems is becoming more important, given changes in the risk picture induced by the move of fish farms into more exposed locations and the impact of rising sea temperatures.

The traditional way of assessing the emergency response capability of a system is through expert opinion and rules based on experience. For example, Wang et al. (2018) determines the emergency response capability for oil-spills in an area based on rules for the necessary amount of available resources. Haixiang et al. (2017) breaks down the rescue capability into subcomponents, and grade them based on expert opinion. A similar approach is used in Kang et al. (2016) where linguistic variables are used to evaluate oil-spill emergency response capability. Omorodion et al. (2021) use expert opinion to assess safety terms of the failure probability of operations performed by Emergency Rescue and

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Abbreviations: DERV, dedicated emergency response vessel; GIS, geographic information system; LNG, liquid natural gas; ECMWF, European Centre for Medium-Range Weather Forecasts.

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https://doi.org/10.1016/j.aquaeng.2022.102243
Received 24 September 2020; Received in revised form 1 March 2022; Accepted 8 March 2022
Available online 12 March 2022

Response Vessels. A method for combining machine learning and historical accident data to predict emergency scenarios, and thereby support emergency response decision-making is presented in Li et al. (2021).

An alternative to experience-based assessment is to test the emergency response performance. Siljander et al. (2015) proposes the use of geographic information system (GIS) based methods for evaluating the response times in maritime search and rescue to support strategic planning in Finnish waters. The presented approach considers weather conditions and vessel types. Zhou et al. (2020) present a three-step framework for assessing maritime search and rescue capabilities, covering response times, demand, and coverage. Response time is estimated using GIS. Simulation models are used to evaluate system design under environmental impacts in Berle et al. (2013), Bergström et al. (2014) and Brachner (2015). Berle et al. (2013) assesses the vulnerability of a maritime liquid natural gas (LNG) transportation system by quantifying the impact of disruption scenarios and mitigating measures. Bergström et al. (2014) proposes an approach for the design of robust arctic maritime transportation systems where the system performance is tested for different ice conditions and ice mitigation strategies. Brachner (2015) presents a model for evaluating the response capacity to helicopter ditches in the Barents Sea for different configurations of response unit positioning over a year with changing weather conditions. The fleet deployment with maximal covering problem and epoch-era analysis is combined in Pettersen et al. (2019) to optimize allocation of emergency response vessels, thereby providing insights into the effectiveness of alternative fleet designs. In another paper, Pettersen et al. (2020) study how latent capabilities can support large-scale emergency response. While they look at the case of the Macondo oil spill, the principle of repurposing assets for novel emergency situations can also be useful in aquaculture, e.g., the role of live fish carriers in emergency response.

This paper contributes to the literature by applying simulation-based performance analysis to determine the emergency preparedness for large scale biomass emergencies in sea-based fish farming. The presented method analyzes three stages of emergency response and covers both non-dedicated emergency response vessels and dedicated emergency response vessels (DERVs). DERVs are not used by the industry today, but could provide additional benefits in emergency response.

2. Material and methods

This section describes the system and emergencies considered, and presents the model structure, model specific temporal definitions and key assumptions. Thereafter, a case study setup is presented, the results of which are given in Section 3.

2.1. Fish farming system and emergency types

Sea-based fish farming systems can be defined as sets of hatcheries, fish cages, slaughterhouses, and vessels, where the vessels constantly change both status and position according to the various operations they perform in the system. Operation types cover daily maintenance and routine tasks performed by small vessels belonging to the location, more complex operations necessitating the assistance of larger external vessels, and finally operations directly handling large volumes of fish which are performed by large, specialized vessels such as live fish carriers. For responding to large-scale fish welfare emergencies, only large vessels handling large volumes of fish are of interest due to the scale of such emergencies.

Therefore, the presented method is intended for live fish carriers, stun & bleed vessels, processing vessels, and the likes. These vessels follow work schedules set up by the fish farmers, meaning that the emergency response capability they provide is time dependent and hard to estimate for a given point in time without considering the dynamics of the system. They may be busy performing planned operations at the time emergency response is initiated, in which case they must complete their current operations before responding to the emergency event. This decision is based on the goal of minimizing loss of fish welfare and end-product quality; aborting an initiated operation is certain to incur an extra load on the fish while the benefit of a quicker response is uncertain. In addition, the vessels may need to recommission before arriving at the emergency location. Recommissioning will depend on organizational resilience and ability to repurpose assets for operations they were not designed for (Pettersen et al., 2020). This may cover change of crew, picking up equipment, supplies, disinfecting the vessel or the likes. Supplementing the emergency response capability with DERVs on stand-by means that there are vessels that are available to respond to emergencies immediately. However, their emergency response contributions still depend on their positions relative to the emergency location and the impact of bad weather conditions.

Examples of emergency types for sea-based fish farming and relevant emergency responses are presented in Table 1. The time frame parameter indicates a rough generalization of how long a situation can be sustained before significant fish welfare consequences are experienced, and amount gives an indication of the possible scope of consequences. Fig. 1 shows the development of three example emergencies as the amount of lost fish as a function of time. The shape and steepness of such development functions in relation to the progress of the emergency response determines the amount of lost fish during an emergency.

2.2. Model structure

The model evaluates the emergency response of the sea-based fish farming system at regular intervals, Δt^{RI}, over a given period $[t_0, t_0 + T]$, as presented in Fig. 2. Emergency response capabilities change as the state of the fish farming system changes with time; therefore, the first step of the method makes a prediction of how the fish farming system develops during normal operation based on the input for the initial state, task schedules and weather covering the period. Emergency response is thereafter simulated, and three emergency response measures are recorded at the different testing times, also referred to as response initiation times, e.g., t_1^{RI} in Fig. 2. The first measure is the first response time, defined as the time it takes from response initiation until the first vessel has commissioned and arrived at the emergency fish farm. The second is the response progress, which covers what response activities that are performed and when, for example the times and amounts for when fish is transported away from the emergency fish farm. Finally, the third is the response completion duration, defined as the time from response initiation until the emergency is over, for example when the last fish is pumped up from the emergency fish farm.

Both the simulation of the normal operations in the fish farming

Table 1
Examples of common fish welfare hazards in sea-based farming of Atlantic salmon, including response measures, typical time frame and scope.

Type	Response	Time frame	Amount
Pancreas disease (PD)	Slaughter	Weeks	One/several farms
Infectious Salmon Anemia (ISA)	Slaughter	Weeks	One/several farms
Lice	Delouse	Weeks	One/several farms
Algae	Slaughter/ Move	Days	One/several farms
Jellyfish	Slaughter/ Move	Days	One/several farms
Oil spill	Slaughter/ Move	Days	One/several farms
Oxygen/ temperature	Slaughter/ Move	Days	One/several farms
Storm/ winter ulcer	Slaughter/ Move	Days	One/several farms

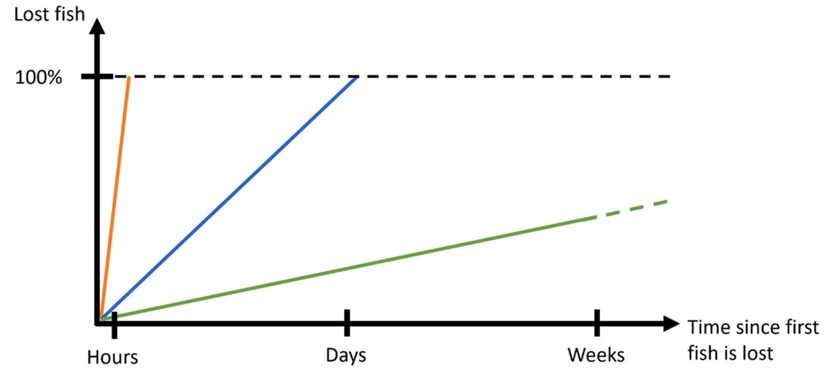

Fig. 1. Examples of simplified linear emergency development functions. Amount of fish lost as a function of time if no emergency response measures are taken.

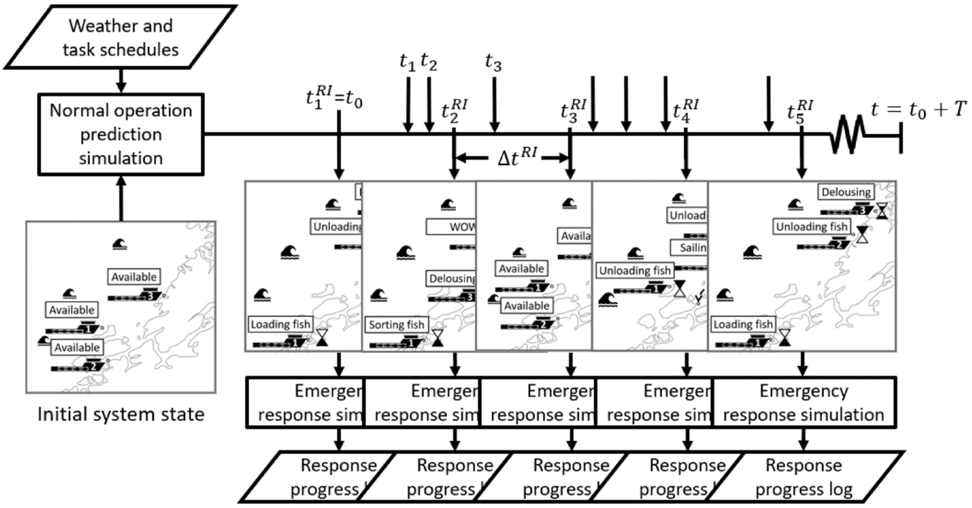

Fig. 2. Conceptual illustration of the method. Based on the initial system state, future system states are predicted, with the system state changing at irregular intervals, e.g., at t_1 and t_2. The response is tested at regular intervals, Δt^{RI}, over the time period T.

system and the emergency response simulation in Fig. 2 are discrete-event simulations where the system state changes at discrete points in time (Henderson et al., 2006; Nelson, 2013). A system state can be illustrated as a snapshot of the system, for example, including the position and status of each vessel and the weather conditions at that point in time, so that the development of a system over time can be described by a series of such snapshots. However, because the simulations are event driven, the system state changes do not occur at regular intervals. The system state is constant for the whole period between two system state changes, e.g., between the event at t_2 and t_3 in Fig. 2. Changes in the system state happens every time a vessel commences or ends a given operation or changes geographical position with more than one nautical mile. Any change in the initial sea-based fish farming system, including changes to the task schedule or the weather time series, will result in a different list of predicted system states. Uncertainty in the evaluation of the emergency preparedness of the system is reduced by applying several sets of historical data for the task schedules and hindcast weather time series.

The emergency response simulation is run once for each simulated emergency event, logging all details of the response. An emergency event is partly defined by the time at which it occurs, thus two identical emergencies occurring at different times are two different emergency events. Hence, every emergency event must be matched with the correct predicted system state for each emergency response simulation.

2.3. *Temporal definitions*

Following an emergency response initiation each vessel has a response duration, T_e^R, defined as the time it takes before the vessel is at the emergency location ready to start emergency response actions. In Fig. 3 response initiation for an emergency event e takes place at time t_e^{RI}, and the vessel takes T_e^R hours to arrive at the emergency location at time t_e^A. The response duration is the result of the time spent on ending the current mission, T_e^M, commissioning to be ready for emergency response actions, T_e^C, and transit sailing to the emergency location, T_e^S. The execution duration, T_e^E, is the time spent on emergency response actions, and varies depending on the emergency, the weather and the vessel's capabilities. Execution duration covers all time activities from the arrival at the emergency fish farm to the response is completed. The response completion duration, T_e^{RC}, is the total time it takes from the response initiation until the response is completed.

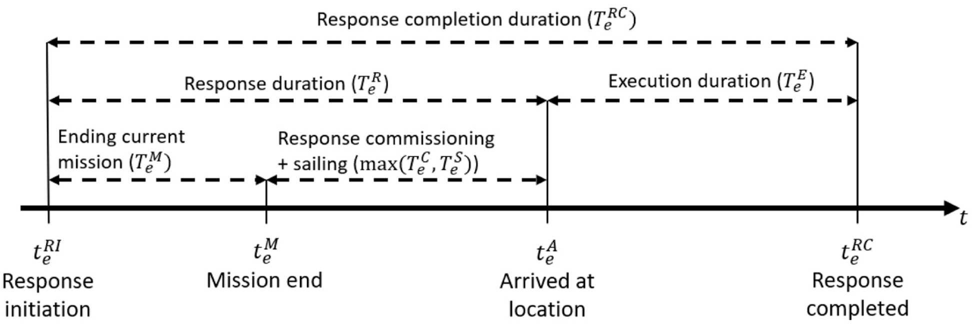

Fig. 3. t_e^{RI} is the time of response initiation for emergency event e. t_e^M is when the vessel is ready to respond to the emergency event. t_e^A is the time at which the vessel has arrived at the emergency location ready to start emergency response actions. The response is completed at t_e^{RC}.

The duration of the response for each vessel depends on its state at response initiation. The main difference between a non-dedicated and a DERV is the response duration T_e^R. In general, the response duration of a DERV will only consist of the sailing duration. In situations where more than one vessel is involved in the emergency response, T_e^{RC} is the result of the combined effort of the fleet. However, since there are limitations on the number of vessels that can operate at a fish farm or at a cage simultaneously, more vessels will not necessarily lead to a reduced T_e^{RC}. How T_e^{RC} is built up of response duration and execution duration differs for each vessel due to different states of the vessels at t_e^{RI}, the vessel characteristics and the weather. In Fig. 4, $t_{e,1}^A$, $t_{e,2}^A$ and $t_{e,3}^A$ indicate the times at which vessel 1, vessel 2 and vessel 3, arrive at the emergency location for emergency event e.

2.4. *Case study setup*

A case study will present how the method can be applied to evaluate the emergency preparedness of a sea-based fish farming system, assessing the three measures: first response time, response progress and response completion duration. First response time is defined as the time until the first vessel is at the emergency location and ready to commence emergency response, as $\min([T_{e,1}^R, T_{e,2}^R, \ldots, T_{e,V}^R])$. This gives valuable insight on how the “responsiveness” of the emergency response changes over time. Response progress provides the details on when the steps of response actions are completed enabling stakeholders to assess the emergency response with respect to how the hazard develops as a function of time, as described in Fig. 1. Response completion duration, T_e^{RC}, is the total time from response initiation until the response is completed and can be compared to the time frame parameter of the hazard to indicate the emergency preparedness.

The case study covers four different setups, varying in geographical size, number and type of emergency resources, and weather conditions, as seen in Table 2. Two configurations of vessel fleets are tested, one with and one without a DERV. Each case is run for a 30-day period and the emergency response is tested every 4th hour. The emergency response is to transport fish to the slaughterhouse from a fish farm approximately ~30 nautical miles (nm) away, for six different volumes of fish to be transported: 100, 400, 800, 1 600, 3 200 and 12 800 tons, respectively.

The small and large geographical areas referred to in Table 2 are presented in Fig. 5, with the corresponding differences in the related infrastructure. For the configurations with a DERV, it is positioned at the location marked “DV” in Fig. 5.

Perfect weather, as specified for case setup 1 and 3, means that the effect of weather is ignored in the emergency response simulation, as opposed to realistic weather where hindcast weather time series affect sailing and operation during emergency response, according to Table 3. The applied weather time series is retrieved from ECMWF’s ERA5 reanalysis through Climate Data Store (ECMWF, 2018) and covers significant wave height for combined wind waves and swell, see Fig. 6. The weather in Fig. 6 is an example of what is experienced at the exposed locations, while more sheltered locations experience lower wave heights.

All the vessels used in the case study are identical live fish carriers

Table 2
Case setup and fleet configurations in the case studies. Two geographical areas of different size with associated fleets of vessels, and two weather situations.

Case setup	Geography size	Weather	# Dedicated ER vessels	# Total vessels
1	Small	Perfect	0/1	3/4
2	Small	Realistic	0/1	3/4
3	Large	Perfect	0/1	6/7
4	Large	Realistic	0/1	6/7

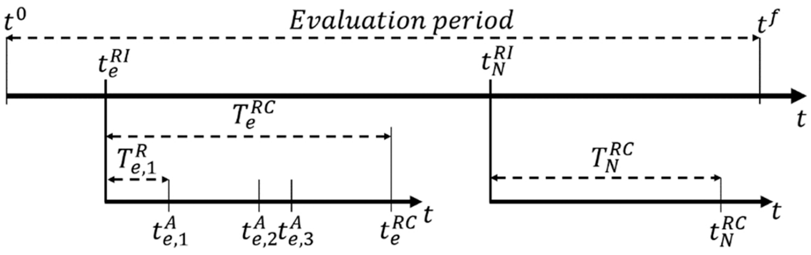

Fig. 4. Relations between time variables when considering more than one vessel and more than one emergency event. $T_{e,1}^R$ is the response duration for vessel 1 in emergency event e, corresponding to the difference between its arrival time $t_{e,1}^A$ and t_e^{RI}.

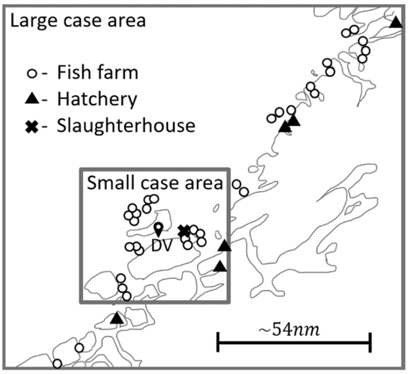

Fig. 5. Geographical areas, and corresponding infrastructure, used in the case study. The DERV is stationed as indicated by "DV". The smaller geographical area is a subset of the larger.

Table 3
Weather factor: effect of weather on sailing durations and vessel operations durations. Duration = expected duration * weather factor.

	$H_s < 0.5m$	$0.5m < H_s < 1m$	$1m < H_s$
Sailing durations	1	1.5	2
Operations durations	1	1.5	*No operation*

with a sailing speed of 13 knots, a carrying capacity of 450 tons of live fish, and a maximum continuous processing rate of 250 tons/hour both for loading and unloading. The given sailing speed is the perfect weather speed, both during normal operations and emergency response, while the achieved speed at any given time is subject to the weather conditions as given by Table 3.

The implemented task schedules are sequences of randomly generated missions, either transporting smolt from a hatchery to a cage in the sea, sorting or delousing aside the cage, or transporting fish from a cage to a slaughterhouse. All cases using the small geographical area use the same task schedules, the corresponding is true for the cases using the large geographical area. This means, for example, that all differences in results between case 1 and case 2 are due to the difference in weather. All vessels start the evaluation period at the location of their first scheduled task. Limitations on the number of vessels that can occupy a location at the same time is only implemented for fish farms at which emergency response is being executed. The implemented response strategy is that all vessels respond as soon as they have completed their current mission and become available for emergency response, meaning that no commenced operations are aborted prematurely.

3. Results

The presented results follow the development of the emergency response, and cover the time measures of first response, response progress and response completion, in that order. Finally, we present an example of how the response measures can be used to evaluate the costs and benefits of emergency response vessels.

3.1. *First response*

First response is a measure of how long it takes before the first vessel in the fleet has commissioned and arrived at the emergency location following response initiation. Fig. 7 shows the first response times of case setup 3 and case setup 4, where the results of the emergency response simulations are indicated every 4th hour of the evaluation period. The x's indicate the first response time of the fleet with no DERV and the circles indicate the first response time for the fleet with one DERV.

We see that the first response times vary more, and are generally higher, for the fleet with no DERV compared to the fleet with one DERV, see e.g. the x's versus the circles in Fig. 7(a), at respective times. This means that for the former the first response time is highly dependent on the time of the response initiation. Including weather effects increases the variation for the fleet with a DERV as seen in Fig. 7(c). In Fig. 7(c) there is a spike at about $t = 620\,hours$ of the evaluation period for the fleet without a DERV, which is the result of several vessels becoming unavailable at the same time from commencing new scheduled operations. Sometimes, the DERV is not the first responder to the emergency, in which case the first response times of the fleet with a DERV and the fleet without a DERV are the same, and lower than that of the DERV. This situation is illustrated by the points that are plotted below the line in Fig. 7(a). These are the results of another vessel happening to be closer to the emergency location, than the DERV is, at the time of the response initiation.

Fig. 7(b) and (d) shows the spread of the first response times for both the fleet with and without a DERV, for case setup 1 and case setup 4. One observation is that the mean response time of the fleets with and without a DERV are close. This may seem to contradict the observation from Fig. 7(a) and (c), however, considering that there are 180 first response times plotted for each fleet in each of the sub-figures, many are on the same line as the circles, only behind them. On the other hand, there are several occasions where the system with no DERV experiences far higher first response times than the average. This is especially prominent for case setup 4 in Fig. 7(d), where the first response time, at one occasion, is

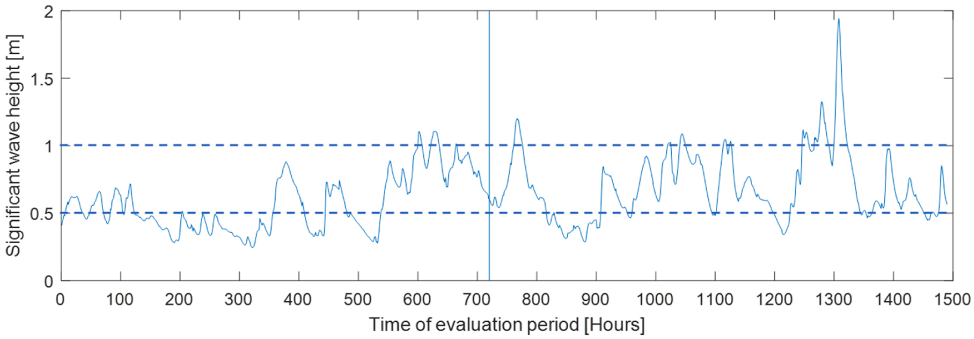

Fig. 6. Significant wave height dataset used in the case study. The evaluation period is $t = [0, 720]$. The remaining weather $t = \langle 720, 1500]$ is needed to play out the emergency responses that last beyond the end of the evaluation period.

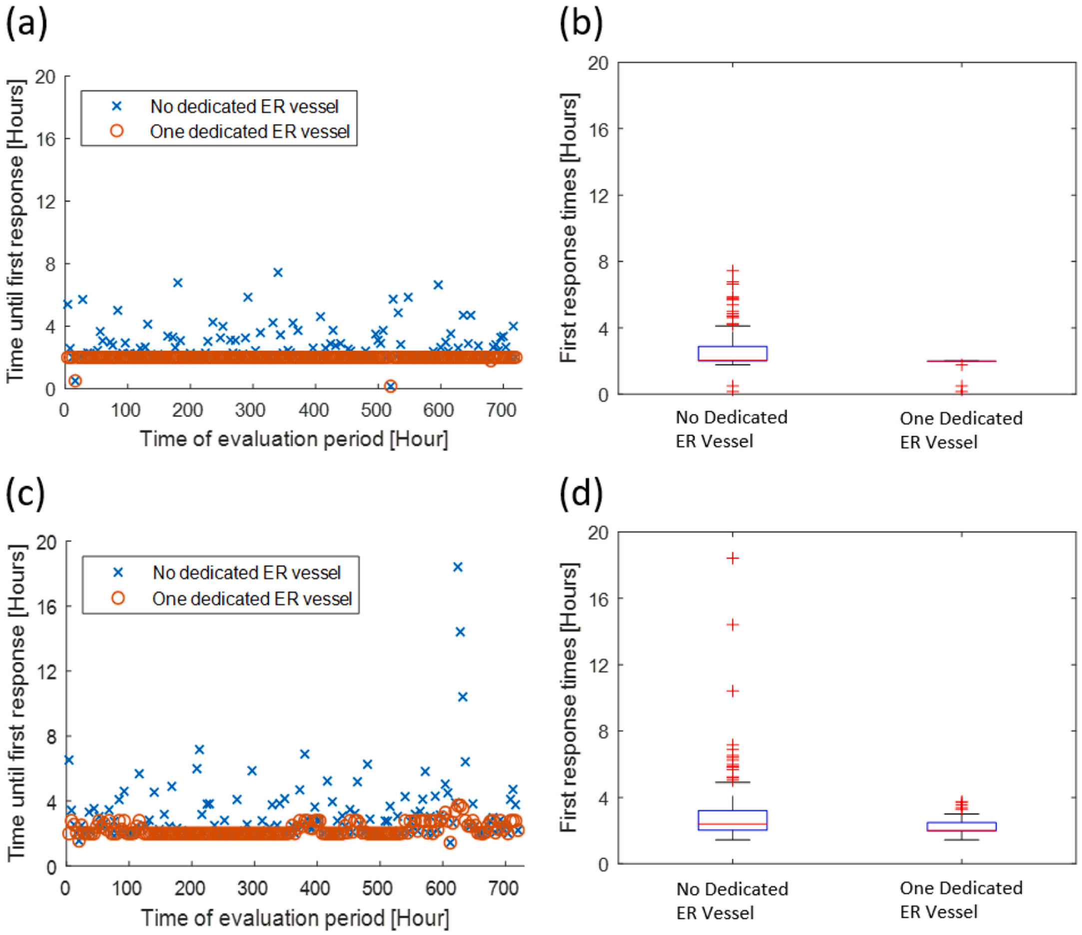

Fig. 7. Time from emergency initiation until the first vessel arrives at the emergency location, every 4th hour of the evaluation period. (a) and (b) case setup 1 – small area, perfect weather. (c) and (d) case setup 4 – large area, realistic weather.

approximately five times the 75th percentile value, meaning that considerable deviations must be expected.

3.2. Response progress

Response progress shows the times of vessel arrivals at the emergency location and the emergency response progress development. Fig. 8 shows the details of the response progress for two different emergency response situations, both with the objective of transporting 3 200 tons of salmon from the emergency location. The arrows indicate the first arrival of each vessel of the fleet to the emergency location, with the downwards pointing arrows being the fleet with a DERV, the first of which is the DERV in both Fig. 8(a) and (b). Response progress is measured as the total amount of fish that has been transported away from the emergency location as a function of time. The response progress must be seen in relation to the emergency development function, see Fig. 1, to determine the quality of the response.

The first observation is that the DERV is the first to arrive in both Fig. 8(a) and (b), and that the fleet with a DERV is the first to complete the response in both cases, respectively 9 and 14 h earlier than the fleet with no DERV. Secondly, the weather delays the emergency response in Fig. 8(b), so that the third vessel of the fleet with a DERV does not start loading fish until $t = t_e^{RI} + 23\mathit{hours}$, even though it arrives at the location at $t = t_e^{RI} + 6\mathit{hours}$. Therefore, in Fig. 8(b), two vessels load at the same time at $t = t_e^{RI} + 23\mathit{hours}$, because both were at the emergency location, only waiting for better weather to start loading fish. A third observation is that the two last vessels have their first arrival at the emergency location much later in Fig. 8(a) than in (b). This is due to the unfavorable position and status of those vessels at $t_e^{RI} = 400\mathit{hours}$ compared to $t_e^{RI} = 616\mathit{hours}$. The fourth observation is that the response progress of the fleet with no DERV and the fleet with a DERV may be very close at times even though the response completion durations for the full 3 200 tons are not.

These results indicate that the benefit of a DERV is more apparent for the response progress than the benefit of shorter first response times would indicate. For example, in Fig. 8(a) the difference in first response times is less than one hour while the difference grows to 9 h towards response completion. This is also true for emergency response in realistic weather where the response is completely halted for some time, see Fig. 8(b).

The results also show that the full evacuation of a mid-sized sea-based fish farm takes in the range of one to two full days. Whether this is acceptable, and the system's vulnerability of the 10-hour gap between the fleets with a DERV and those without, must be seen in relation to the

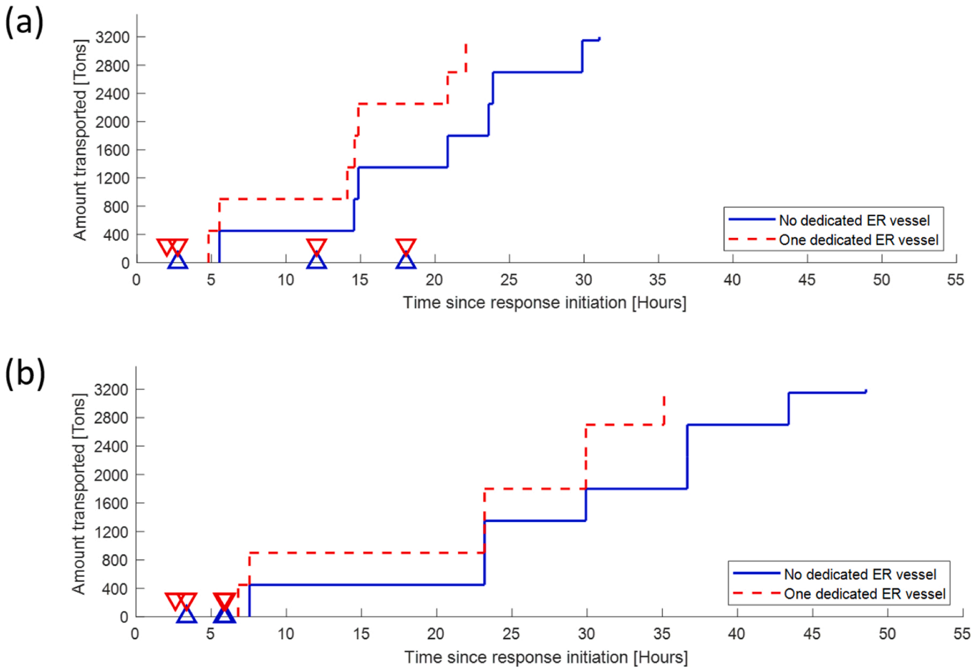

Fig. 8. Response progress for two selected emergency events. Dashed line and downwards pointing arrows indicate fleet with a DERV. (a) case setup 1. Small area, perfect weather. $t_e^{RI} = 400$ hours into the evaluation period. (b) case setup 2. Small area, realistic weather. $t_e^{RI} = 616$ hours into the evaluation period. The arrows indicate the first arrival for each vessel at the emergency fish farm.

implementation of early warning systems for the relevant emergency event and how far the situation has developed before the response is initiated.

3.3. *Response completion*

Fig. 9 shows the response completion durations, T_e^{RC}, for transporting 3 200 tons of fish away from an emergency location, for case setup 2 and case setup 4.

The first observation is that the difference between the fleet with and without a DERV is clearer for case setup 2, in Fig. 9(a) and (b), than for case setup 4, in Fig. 9(c) and (d). It is also evident that the large system has a significantly lower response completion duration, in general. Both observations match the expectations well considering that more vessels contribute in the emergency response in the large system, and that the relative contribution of the DERV therefore is lower. This effect is dependent upon the system's capability to utilize the higher number of emergency response vessels, which in turn is given by the physical constraints on, e.g., how many vessels that can operate at the farm simultaneously. If the limit is reached, so that the emergency response vessels are not fully utilized, a line corresponding to the lower limit for the response completion duration appears in the plot, as seen in Fig. 9(c) between $t = 120$ and $t = 350$. Increasing the number of emergency response vessels will drive the response completion durations at all times of the evaluation period towards that line, which is around 12 h, in Fig. 9(c). However, the effects of harsh weather conditions during the emergency responses affects the marginal change from adding an emergency response vessel and may even establish a higher limit, e.g., if t_e^{RI} is at a time when the weather does not allow for operations to be commenced. Finally, as expected the variations in the response completion durations closely follow the development of the weather conditions in Fig. 6.

3.4. *Emergency consequences*

Consider a simplified emergency where a fish farm holding 3 200 tons is exposed to an algae bloom taking out all fish that remains in the fish farm more than 24 h after the response initiation, a realistic scenario during the algae bloom in Northern-Norway in 2019 (Vikøyr and Oddstad, 2019). Table 4 presents the resulting consequences of the emergency in case setup 2 and 4 based on the 180 emergency preparedness evaluations that were performed with 4-hour intervals over the evaluation period of 30 days.

4. Discussion

Understanding emergency preparedness is crucial both to ensure good fish welfare and a sound operational practice in sea-based fish farming. The insight gained from model-based simulations enables the stakeholders to quantitatively assess their ability to effectively handle the various situations that might arise, and how to prepare for such situations. Based on the results of the case study, the method can be used to evaluate both the responses to individual emergencies and the general emergency preparedness level of a fish farming system. It can be used to indicate how well a basic operational system is set up for emergency response, and the improvement in emergency response capabilities from having additional emergency response resources. In Table 4, we see that the effect of having a DERV is more significant for the smaller system, which is expected as the relative capacity of an extra vessel is higher than in the larger system, and the emergency does not scale with the system size. Whether the first response times, response progress or response completion durations advocate for additional resources or other measures must however be seen in relation to specific emergency events and their required response times and statuses. A cost-benefit analysis of possible emergency response measures, for instance adding

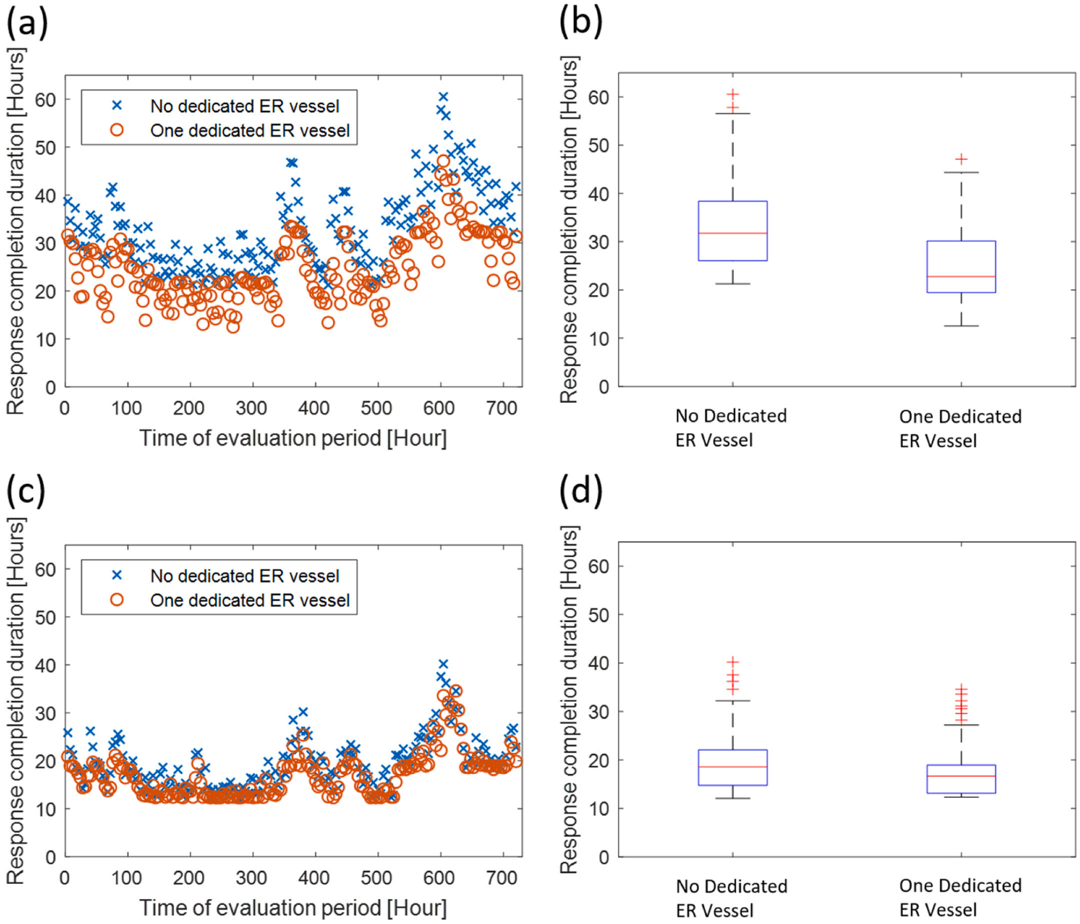

Fig. 9. Response completion durations for transporting 3 200 tons of fish away from the emergency location to the slaughterhouse. (a) and (b) show case setup 2 – Small system, realistic weather. (c) and (d) show case setup 4 – Large area, realistic weather.

Table 4
A complete rescue means that all the fish was moved before the 24-h limit. Average loss is the total loss of all 180 evaluations divided by 180. Max loss is the result from the worst performing evaluation out of the 180.

Case setup	Complete rescues (out of 180)	Average loss of biomass	Max loss of biomass
2 (no DERV)	29 / 180 = 16%	966.67 = 30%	2750 = 86%
2 (one DERV)	97 / 180 = 54%	341.11 = 11%	2300 = 72%
4 (no DERV)	149 / 180 = 83%	139.17 = 4%	2300 = 72%
4 (one DERV)	168 / 180 = 93%	59.72 = 2%	1850 = 58%

a DERV, would be one way to make such evaluations. However, formulating a cost benefit analysis is not straight forward due to both the cost and benefit side being highly dependent on, e.g., the system boundaries and to what degree a vessel is going to be dedicated.

Testing for two different system sizes is of interest because regulations can divide fish farms into geographical areas, e.g., in the case of Norway where there are defined production areas. Biosecurity restrictions related to crossing the production area borders can be both costly and time consuming. This means that response vessels, to a large extent, can be assumed not cross production area borders within the time span of an emergency response situation.

Given quick response initiation the emergency response of most of the tested cases could be characterized as acceptable, based on the time frames of Table 1. For both weather scenarios and system sizes, the longest response completion durations for emergencies up to 3200 tons were in the order of two days. However, for the 12 800 tons emergencies, response completion durations were found to be as high as a week. The case results could be regarded as optimistic bounds as the response strategy made all vessels respond to the emergency event. Also, the results are based on predictions of the vessel activities, i.e., the mission schedules. New missions may suddenly arise, and the weather forecasts are not certain. The further into the future the evaluations go, the more uncertain are the predictions. However, the assumption that commenced operations may not be aborted prematurely might make the vessels less responsive than they are in reality.

In a real-life scenario, two conditions are likely to delay the emergency response, making the response times longer than shown in the results. First, the hazard must be identified, and then the appropriate decision makers in the companies must decide to implement response actions. Early detection of HABs is not easy as the identification of the algae type and concentration usually is done by taking water samples and sending them to laboratories for analysis (Mowat and Chadwik, 2021). Systems for early detection based on satellite imaging of algal concentrations, artificial intelligence identification of algae types, and monitoring of the potential for algal blooms are being developed (Davidson et al., 2021; Mowat and Chadwik, 2021; Osnes, 2019). Potential for algal blooms is evaluated based on secondary indicators such as water temperature, oxygen levels and the level of blue-green algae. After a threat or unwanted event has been identified emergency response resources are not deployed until the appropriate decision makers give the order. In situations like severe HABs, the potential large scale of the required emergency response means that the response is costly and is likely to negatively affect other parts of the business, e.g., occupying company resources that are needed in normal operation. This means that a thorough assessment of the situation must be made before initiating a full emergency response, and action may not be deemed beneficial until the emergency has escalated.

Considering the two delaying factors in real-life situations, response time could probably be improved if DERVs were positioned according to real-time assessments of harm potential and the probability of an emergency. Such a problem would resemble the maximal covering problem addressed in (Pettersen et al., 2019) Probability of emergency could, e.g., be based on the degree to which environmental conditions favor a HAB, as proposed in (Mowat and Chadwik, 2021).

Insurance companies provide insurances against losses related to natural events such as algae blooms. Analyses of emergency response performance can be useful in understanding and quantifying risk (Holmyard, 2017). Enabling operators to show insurers that they reduce the consequences of adverse events can also provide benefits for both parties.

Stakeholders should be aware that the method is not meant to give exact information far into the future, rather it is meant to indicate the emergency preparedness level of a sea-based fish farming system. Therefore, a sufficient number of evaluations should be performed, with different input data, so that they trust the results and the value of the information in the results. However, this depends on what the interests of the stakeholders are and what they want to study. If testing for general preparedness, then the uncertainty of task schedules and weather forecasts is less of a problem since hindcast data can be used. If they want to perform what-if analyses on specific emergencies, the evaluation period should not be stretched too far.

5. Conclusion

The method presented in this paper is suited for assessing the emergency preparedness for large-scale fish welfare emergencies in sea-based fish farming. It provides a useful way of studying the time-dimension for emergency preparedness needs and resources in sea-based fish farming by giving information on the three response measures; first response times, response progress and response completion durations, enabling decision makers to perform detailed analyses to determine the emergency preparedness of any given sea-based fish farming system. The method also provides information which can be used in cost benefit analyses to evaluate the implementation of emergency response measures.

The results of the test cases indicate that the emergency preparedness of large sea-based fish farming systems with many vessels is better than for smaller systems with fewer vessels. They also show that when there are fewer vessels that can contribute to the emergency response, a dedicated emergency response vessel can have a more significant impact on the response completion. First response times and response completion durations are strongly time dependent for systems without a DERV, and the time dependency increases with realistic weather. In the small system, the DERV effectively creates an upper boundary for the first response times, while for the large system there is still some spread towards longer response times. However, the most extreme outliers are effectively reduced with the introduction of the DERV. The effect of a DERV on the response completion duration depends on the relative capacity increase it represents in the system.

CRediT authorship contribution statement

Hans Tobias Slette: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Bjørn Egil Asbjørnslett**: Conceptualization, Writing – review & editing, Supervision. **Sigurd Solheim Pettersen**: Writing – review & editing. **Stein Ove Erikstad**: Conceptualization, Software, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been funded by the Research Council of Norway, grant number 237790, through SFI EXPOSED Aquaculture Research Centre. The funding source had no influence on the research or the preparation of the article. The authors would like to thank Dagfinn Breivik Skomsø and Barbo Klakegg at Åkerblå for support in understanding the fish welfare hazards.

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Research paper 4

Effective utilization of service vessels in fish farming: Fleet design considering the characteristics of the locations

Slette, H.T.; Asbjørnslett, B.E.; Fagerholt, K.; Lianes, I.M.; Noreng, M.T.
Aquaculture International, 2022

Aquaculture International
https://doi.org/10.1007/s10499-022-00974-9

Effective utilization of service vessels in fish farming: fleet design considering the characteristics of the locations

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Received: 18 November 2021 / Accepted: 2 September 2022

Abstract

Effective utilization of service vessels in sea-based fish farming requires that the vessels are suited to the operating environments at the fish farms. This paper presents a methodology for assessing service vessel fleet performance when serving a network of farms with different metocean conditions. Fleet performance is defined as the ability to perform operations requested by the fish farms, in due time. An optimization for simulation approach is employed, implementing a routing and scheduling heuristic developed for aquaculture service vessels. A case study was performed assessing the performance of two different fleets serving a set of 21 fish farms. The variation in local metocean conditions between the farms, and how weather changes in time, challenges the operability of the aquaculture infrastructure and the effective routing and scheduling of the vessels. Hence, the results show that proper fleet composition in this context improves fleet performance. Fleet performance is substantially higher when fleet composition, routing, and scheduling is based on the specific weather conditions.

Keywords Sea-based fish farming · Weather exposure level · Location environment · Fleet performance · Routing and scheduling · Simulation

Introduction

Sea-based farming of Atlantic salmon has seen almost a sevenfold increase in production volumes in Norway from 1998 to 2020 (Norwegian Directorate of Fisheries, 2021a). Ever larger cages have been installed at new locations, often with higher weather exposure. With the introduction of the development license scheme in Norway (Norwegian Directorate of

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Handling Editor: Gavin Burnell.

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Fisheries, 2021b), the industry started a transition towards more exposed locations with even larger cages and infrastructure resembling offshore structures from oil and gas (Bjelland et al., 2016; Nordlaks Produkter AS 2021; Norway Royal Salmon ASA, 2020; Nova Sea AS 2021; SalMar ASA 2020) . Expansion into new areas, especially areas with challenging weather conditions, involves a site selection process including multi-criteria evaluations considering environmental, economic, and social aspects (Chahinez et al., 2020; Dapueto et al., 2015; Pérez et al., 2005). The effect of the environment on the fish, and the effect of the production on the environment, is extensively studied in the literature (Dunne et al., 2021; Frankic & Hershner, 2003; Holmer, 2010; Hvas et al., 2020). However, how the environment affects the operation of fish farms, and in particular the vessel operations, is less studied. Sea-based fish farms are geographically spread and have different metocean conditions, which result in differences in the environmental loads at the farms (see Fig. 1). This covers both the simultaneous weather and the long-term statistics. Even for fish farms that are close to each other, the local geography can affect the weather to the extent that there is little correlation between the weather at the farms. A given set of fish farms are supported by a specific fleet of vessels with various designs that have different capabilities and seakeeping abilities. Vessel operations are performed if the weather conditions at the location are acceptable. Overall performance of a set of fish farms is dependent on the capability of the fleet of vessels to perform vessel operations at the farms given the weather at the locations.

Full utilization of the service vessel feet is only achieved if the vessel fleet routing, scheduling, and deployment is optimal, and able to consider the stochastic nature of operation requests from the farms and the weather at the locations. This entails that the operation of the service vessel fleet is not a question of making the right or wrong decisions, but it is an optimization problem weighing operating costs against operational performance (Lianes et al., 2021).

The interaction between vessel and fish farm infrastructure, and how it is affected by weather is studied in detail (Shen et al., 2019b, 2019a; Shen et al., 2018a; Shen, Greco, Faltinsen, et al., 2018b). Operational performance of single vessels in terms of operability

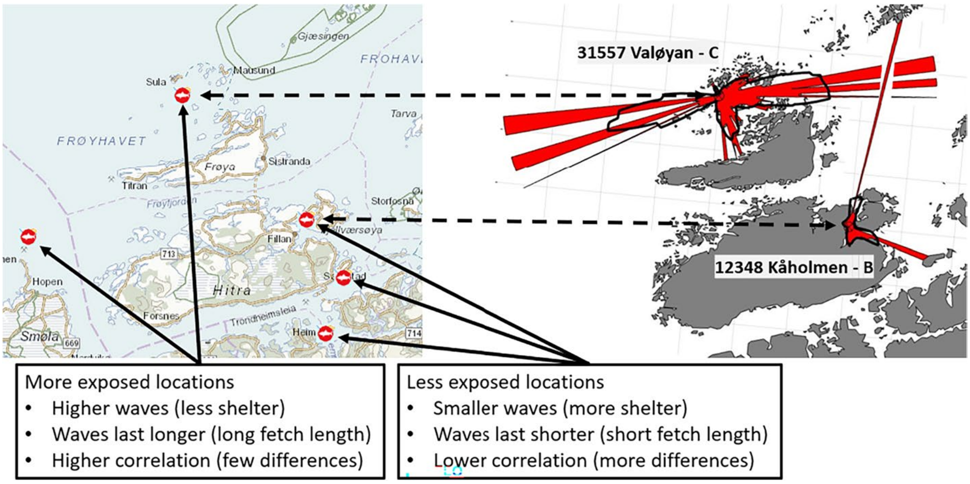


Fig. 1 A summary of typical differences between less and more exposed fish farms. The right-hand side illustrates fetch lengths for the Valøyan and Kåholmen locations. That is, how waves can build up before reaching the farm. Left-hand map is retrieved from the Norwegian Directorate of Fisheries (2021a)

is studied for other maritime industries, including percent operability based on scatter analysis (Gutsch et al., 2016; Tezdogan et al., 2014), the relative rate of operation based on discrete-event simulation (Sandvik et al., 2018), and the operability robustness index (Gutsch et al., 2020). For other segments, such as traditional shipping, the literature also covers long-term operational performance of fleets of vessels in the context of strategic problems such as the maritime fleet size and mix problem (Álvarez et al., 2011; Pantuso et al., 2014; Sperstad et al., 2017), and short-term maritime fleet routing and scheduling (Álvarez, 2009; Lianes et al., 2021; Psaraftis, 2019).

The research question of this paper is how weather conditions affect service vessel fleet performance in sea-based fish farming. In answering this question the paper contributes to the literature by (1) establishing a method for assessing the effects on fleet performance and (2) quantifying the effect on the fleet performance from selected variations in weather conditions. Assessment of service vessel fleet performance is methodologically based on an operations research approach adapting a rolling horizon framework employing optimization for simulation. The methodology is developed to enable scenario testing.

Materials and method

The solution method is based on testing the fleet performance for different fleets and weather scenarios, and then analyzing the variations in performance. Testing of a single fleet and weather scenario is performed by simulating operation of the fleet for a given time period, serving a set of fish farms according to their requests for vessel operations. Fleet performance is defined as the portion of the requested operations that the service vessel fleet manages to perform within the given time windows. A weather scenario is a time series of the weather at each considered fish farm covering the complete chosen time period. Optimization for simulation (Fu, 2002) is applied, with discrete event simulation, in a rolling horizon framework where new information on weather forecasts and requested operations are revealed at fixed intervals (Fagerholt et al., 2010; Fu, 2002) (see Fig. 2). The heuristic of Lianes et al. (2021) optimizes routing and scheduling of the vessels.

Every time the sub-problem is solved, the total period of the rolling horizon is divided into four; the fixed, central, forecast and far future periods (see Fig. 3). The fixed period covers what has already happened, the central and forecast periods together make up the

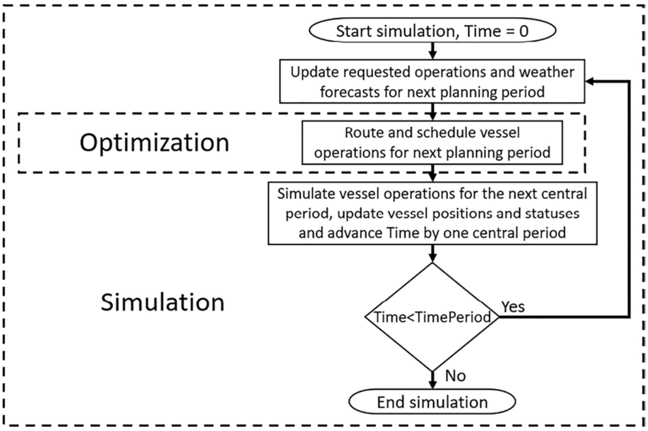


Fig. 2 A flow chart of the optimization for simulation procedure with rolling horizon. Optimized routing and scheduling for vessel operations are generated at fixed intervals for the complete duration of the rolling horizon

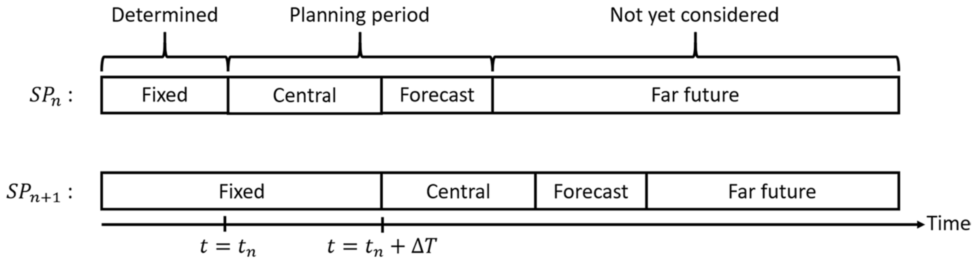


Fig. 3 The relation between the periods in a rolling horizon. Inspired by (Brevik et al., 2020). Sub-problem n (SP_n) is solved at time $t = t_n$, while sub-problem $n + 1$ (SP_{n+1}) is solved at time $t = t_n + \Delta T$, where ΔT is a fixed duration

planning period which is the period the sub-problem is solved for. Finally, the far future period covers the future beyond what is considered in the sub-problem. Sub-problem $n + 1$ (SP_{n+1}) is solved at the end of the central period of sub-problem n (SP_n) (see Fig. 3). The reason that the planning period is longer than the central period is to avoid solving it in a way that is disadvantageous to the long-term objective. Furthermore, the length of both the central period and the forecast period is a compromise between computational time and solution quality (Andersson et al., 2015; Stolletz & Zamorano, 2014).

The behavior of the service vessel fleet is simulated for the duration of the central period after solving a sub-problem. When solving SP_{n+1}, the resulting vessel positions and statuses from the simulation that followed the solution of SP_n is used as initial vessel positions and statuses. The objective function of the sub-problem is to maximize the number of completed operations, considering all operations as equally important and disregarding costs. This is a modification from the objective function used in Lianes et al. (2021) where a more realistic system of profits and costs is used, and where the various operations are given different priorities. The modification of the objective function to only return one parameter, is made to minimize ambiguity in the comparison of the fleet performance of the different fleets and weather scenarios. For details on the heuristic solving the routing and scheduling sub-problem, see Lianes et al. (2021).

Design of experiments

A case study assesses how the performance of two different fleets of service vessels change for different weather scenarios, and the length of the operation time windows. First, the details of the studied system are presented before the different weather scenarios and time window lengths are described. An experiment is one combination of vessel fleet composition, weather scenario and time window length.

The studied system: a system of fish farms of varying exposure level

The study covers 21 sea-based fish farms off the Norwegian coast (see Fig. 4). The shortest sailing distance between any two farms is less than 1 nautical mile and the longest is approximately 58 nautical miles. All the fish farms are assumed to be identical with respect to size and technical solutions, having a total capacity of 3120 tons each and consisting of flexible, open net pens.

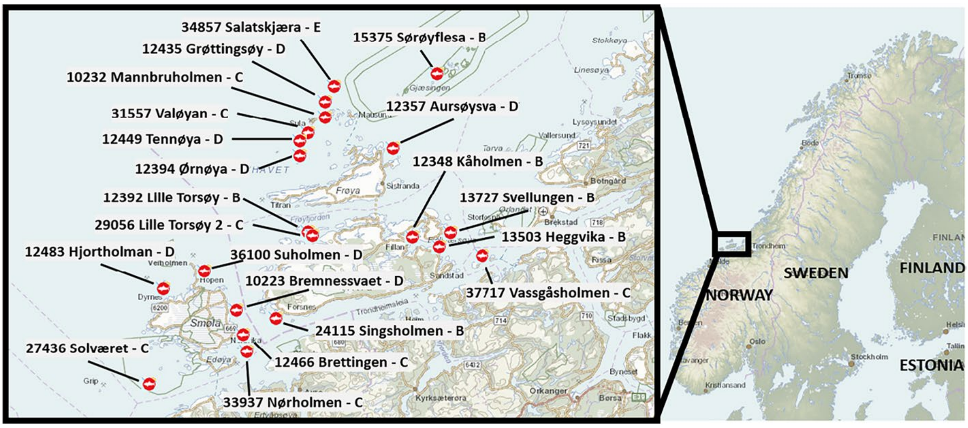


Fig. 4 Number, name, and wave class of the 21 considered fish farms off the mid-west coast of Norway. Maps are retrieved from the Norwegian Directorate of Fisheries (2021a)

In Fig. 4, the number, name, and wave class of each fish farm is presented, with the latter being based on the 1-year significant wave height (H_{s1year}) and wave peak period (T_p) (see Table 1). There are five wave class levels according to a definition in the appendix of Standards Norway (2009), ranging from A "Low exposure" to E "Massive exposure." The wave class of the fish farms are based on 16-year wind wave time series generated using fetch analysis (Lader et al., 2017). Fetch analysis is using the distance from the farm to nearest land in the various directions to analyze the build-up of waves. It is worth noting that the fish farms in the study cover the range from "Moderate exposure" to "Massive exposure," and that most fish farms have "Large exposure" or higher.

At each fish farm the time between two consecutive requests for the same operation type is exponentially distributed with a mean of 14 days. Vessel operations are only performed if the wave height does not exceed the operational limit of 0.5 m. This entails that the wave height is the only weather parameter considered in the study. The limit is chosen based on the practice at a specific fish farm, according to conversations with the personnel at the farm. However, it should be noted that in practice the exact limit is not strictly enforced due to the variations and inaccuracy in the subjective perception of the weather.

The duration of the operations is 4 h, which means that a weather window of at least 4 h is needed to perform an operation. A weather window is a period of consecutive sea states that do not exceed the operational limit (Det Norske Veritas AS 2011). Operations are usually required to be performed within some reasonable time relative to the time of the request, often referred to as the time window of the operation. This is the period within

Table 1 Wave class definitions for 1-year significant wave height (H_{s1year}) and peak period (T_p), borrowed from the appendix of Standards Norway (2009). Translated from Norwegian

Wave class	$H_{s1year}[m]$	$T_p[s]$	Designation
A	0.0 – 0.5	0.0 – 2.0	Low exposure
B	0.5 – 1.0	1.6 – 3.2	Moderate exposure
C	1.0 – 2.0	2.5 – 5.1	Large exposure
D	2.0 – 3.0	4.0 – 6.7	High exposure
E	> 3.0	5.3 – 18.0	Massive exposure

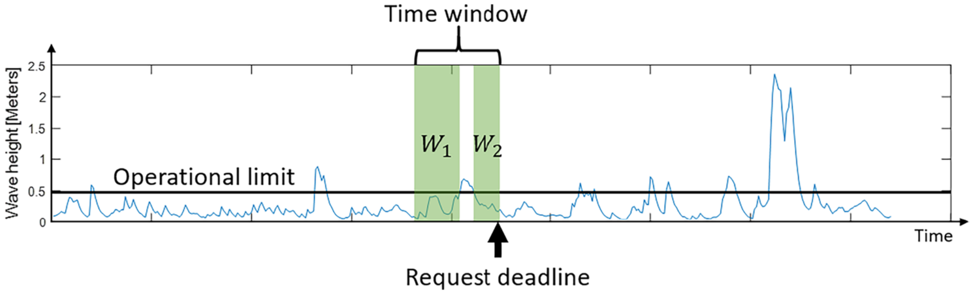


Fig. 5 Illustration of how weather windows (W_1 and W_2) are found based on time window, operational limit and weather condition. The time window describes a period within which the operation can be started, and the operational limit and weather further restrict possible starting times

Table 2 Overview of the considered vessel types, including what operations they can perform and their designation

Vessel type	Can perform operation type	Vessel designation
1	1, 2, 3	Multi-purpose
2	1	Specialized
3	2	Specialized
4	3	Specialized

which the operation can be initiated, and it ends at the time of the request (see Fig. 5). Three different time window lengths are tested in the study: 3, 6, and 9 days.

Four vessel types are included in the study, composing two different fleets:

- One homogeneous fleet of multi-purpose vessels.
- One heterogeneous fleet of specialized vessels.

The homogeneous fleet consists only of vessels of type 1, while the heterogeneous fleet consists of vessels of types 2, 3, and 4 (see Table 2). Three operation types are considered, referred to as types 1, 2, and 3, and they differ only in terms of the required functionality a vessel must have to perform them. Vessel type 1, the multi-purpose vessel, can perform all three operation types, while vessel types 2, 3, and 4 are only able to perform one each: operation types 1, 2, and 3, respectively.

Weather scenario variations

A 16-year wind wave time series generated for each fish farm by Lader et al. (2017) is the basis for the weather scenarios used in the experiments. The time series consists of 6-h sea states, which means that the weather is the same for 6 h at the time.

This paper investigates the effects of three ways in which the weather scenarios can vary. Variation 1 is change in exposure level, which corresponds to change in the average wave height. Variation 2 is change in continuity, which corresponds to change in how the wave height is distributed in time. Finally, variation 3 is change in correlation, which is the correlation in wave height between the fish farms. The variations are chosen because they cover important aspects of the differences between sheltered and exposed fish farms (see Fig. 1).

Higher waves are expected when moving further offshore, longer fetch lengths means that the sea takes longer to calm, and the correlation between the farms is higher for exposed farms because there are fewer geographical elements creating local conditions.

Variation 1: change in exposure level

Weather scenarios at the fish farms are changed by multiplying all sea states in the time series with a factor, either increasing all wave heights or reducing them. Three exposure level modifiers are introduced: low, medium, and high. Low corresponds to a reduction of the wave class of each location by one step, and the high corresponds to an increase of one step. That is, in the low modification a location which has “Large exposure” according to the original wind wave time series is changed so that it has “Moderate exposure” instead. This is achieved by multiplying each element of the time series with a constant corresponding to the relation between the two wave classes according to the definition in Table 1. In the case of going from “Large exposure” to “Moderate exposure,” the factor is 0.5. The same logic is applied when increasing the wave heights to get the high exposure level modification. The medium modification entails no such change to the wave height time series. Figure 6 shows the three modifications for the Bremnessvaet fish farm, where the middle graph is the wave height time series with the medium modification. Bremnessvaet has “High exposure” originally, meaning that low modification gives “Large exposure,” and high modification gives “Massive exposure.” These are the lower and upper graphs in Fig. 6, respectively.

Variation 2: change in continuity

Continuity describes to what degree waves build up and accumulate, according to the relation in Eq. 1. The wave height in the i th sea state, H_i, is a function of the wind waves of the same sea state, H_i^w, and the wave height in the previous sea state, H_{i-1}. This means that the wave height in a 6-h period is a function of the waves in the previous 6-h period and the waves made from the wind in the current 6-h period. The continuity, C in Eq. 1, is a number between 0 and 1 determining the portion of the wave energy that is carried over from the previous sea state. A higher C-value results in waves taking longer to dissipate, and the waves being higher on average.

$$H_i = \sqrt{H_i^{w2} + CH_{i-1}{}^2} \tag{1}$$

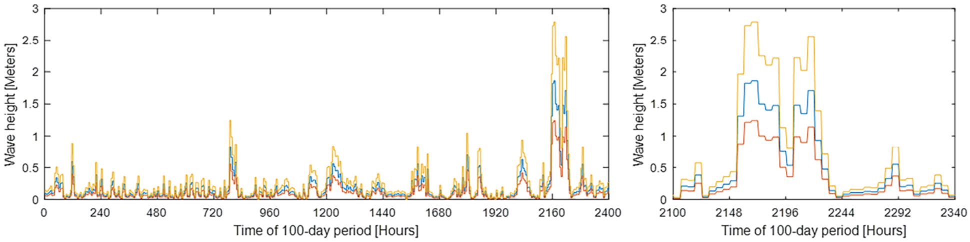


Fig. 6 Illustrating exposure level modification of a 100-day sample of wave height at Bremnessvaet. The middle line is the medium modification, while the lower and upper lines are low and high, respectively

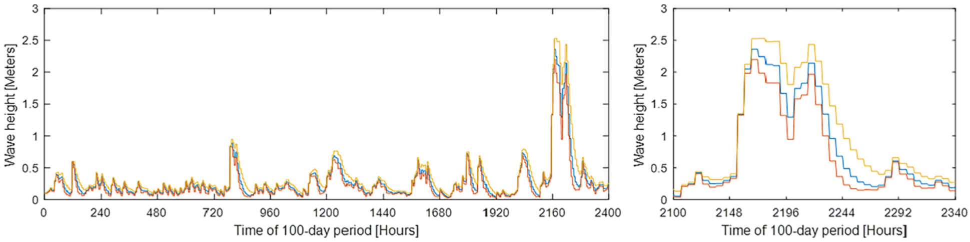
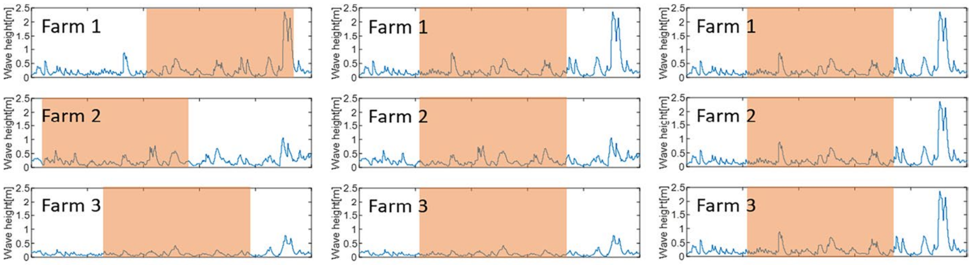


Fig. 7 Illustrating continuity levels for a 100-day sample of wave height at Bremnessvaet. The lower, middle and upper graphs have 35%, 50%, and 65% continuity, respectively. All three have medium exposure level modification



(a) Reduced correlation (b) Normal correlation (c) Full correlation

Fig. 8 Illustrating differences between correlation levels. Fish farms experience the highlighted period of the time series. For reduced correlation the farms experience different periods from different time series, while for normal correlation the farms experience the same period from different time series. Full correlation gives the exact same weather to all locations

Three levels of continuity are studied: 35%, 50%, and 65%. All fish farms share the same continuity level in each case. This is a significant simplification with respect to the real-world behavior where the extent to which a wave state affects the next depends on several factors such as the local geography, the magnitude and direction of the former wave state, and the magnitude and direction of the current waves (Holthuijsen, 2007). However, this coarse approximation does give the desired modification to the wave height time series, as seen in Fig. 7 where the 35%, 50%, and 65% continuity levels of Bremnessvaet are presented for the medium exposure level modification. Comparing the graphs to the middle line of Fig. 6, which has 0% continuity, the waves are higher, and they take longer to dissipate. This is amplified for higher continuity levels, resulting in longer “tails.”

Variation 3: change in correlation

The waves at the fish farms are somewhat correlated because all the farms lie within a relatively small area. However, the waves are also affected by local conditions that differ for each fish farm. The three correlation levels considered in the study are reduced, normal and full correlation, with normal correlation being the actual correlation between the fish farms. This means using samples of the time series from the same time period for all the fish farms (see Fig. 8 (b)). The reduced correlation level selects samples for the fish farms from different periods (see Fig. 8 (a)). The full correlation level uses the exact same weather for all fish (see Fig. 8 (c)).

Experiment design summary

Table 3 presents a summary of the parameters that are varied in the case study. An experiment is defined by the levels for the different parameters, giving a total of 162 possible experiments while the weather scenarios are based on the exposure level modification, continuity level and correlation level, giving a total of 27 different weather scenarios. Each experiment is simulated for a 100-day period, with a 3-day central period and a 2-day forecast period. Each experiment is tested for five different realizations of operation requests, and the average performance is presented as the result for the experiment.

Results

Variations in weather scenarios among the fish farms affect fleet performance. Magnitude and specifics of the effects depend on fleet composition and length of time windows. First, the performance of the two different fleets is presented for changes in weather scenarios. Then, the performances of the same fleets are given for variations in time window lengths, for a selection of weather scenarios. Finally, fleet performance is described for different fleet sizes. The multi-purpose fleet (MP) consists of three vessels of vessel type 1, and the specialized fleet (SPZD) consists of three vessels, one of vessel type 2, one of type 3, and one of type 4.

Varying weather scenarios

The multi-purpose fleet performs better than the specialized fleet for all weather scenarios. Figure 9 presents the results for 3-day time windows, and all considered variations in weather conditions. The results are consistent in that higher exposure level modification or increased continuity always gives a reduction in performance. Negative effects on performance seems to be amplified between continuity and exposure level. That is, effect of changes in continuity are larger for larger exposure level modification, and effect of changes in exposure level modification is larger for higher continuity.

Higher correlation is not necessarily negative as both fleets, in most cases, perform better with normal correlation than reduced correlation. On the other hand, there is a significant reduction in performance for full correlation.

Table 3 Explanation of the parameters that are varied between the experiments. Levels (modifiers) describe what values the parameters can take

Parameter	Description	Levels (modifiers)
Exposure level	1-year significant wave height	Low, medium, high
Continuity	Energy carry-over from previous sea state	35%, 50%, 65%
Correlation	Similarity in wave height development	Reduced, Normal, Full
Time window length	Period within which an operation can be initiated	3, 6, 9 days
Fleet composition	The only vessel type in the fleet	Multi-purpose, specialized

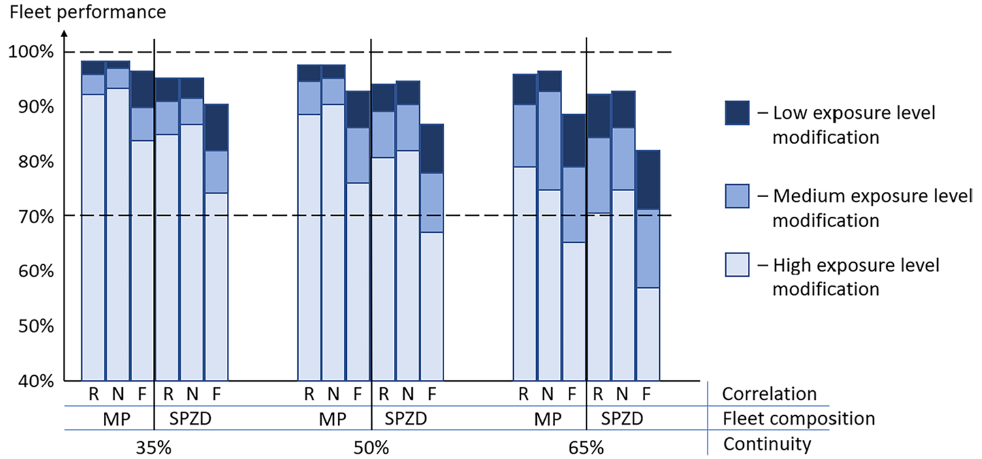


Fig. 9 Achieved fleet performance for 3-day time windows and variations in correlation, fleet composition, continuity, and exposure level modification. R, N, and F designate reduced, normal, and full correlation, respectively. For fleet composition, MP means multi-purpose and SPZD means specialized. Both the multi-purpose and specialized fleets consist of three vessels each. Bars in darker shades are placed behind the ones in lighter shade, and are thus taller

Varying time window length

Longer time windows improve fleet performance, and the effect is larger for high exposure level modification and full correlation (see Fig. 10). In addition, the specialized fleet seems to be slightly more sensitive to variations in time window durations than the multi-purpose fleet. Changes in time windows give approximately the same absolute effects for all three levels of continuity, across other weather characteristics and fleet composition.

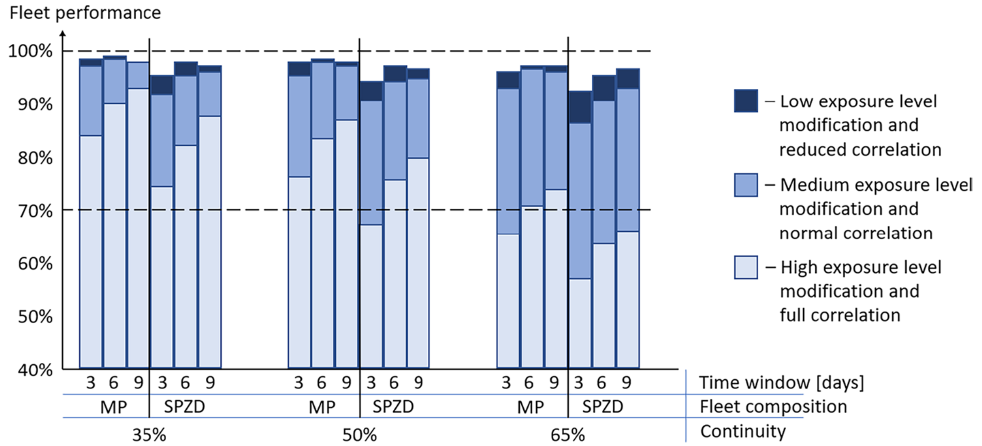


Fig. 10 Achieved fleet performance for selected combinations of exposure level modification and correlation, and for all combinations of time window duration, fleet composition and continuity. For fleet composition, MP means multi-purpose and SPZD means specialized. Both the multi-purpose and specialized fleets consist of three vessels each. Bars in darker shades are placed behind the ones in lighter shade, and are thus taller

That is, e.g., increasing the time window duration from 6 to 9 days yields the same percentage point increase in performance for the lightest shade, 35%, MP-bars as for the lightest shade, 65%, MP-bars. Longer time windows can to some degree compensate for change in continuity. For 35% continuity longer time windows can almost compensate for increased exposure level modification and correlation.

Varying fleet size

More vessels will never have a negative impact on fleet performance. However, the marginal contribution of each extra vessel decreases rapidly and seems to converge. Figure 11 presents the fleet performance of fleets of multi-purpose vessels, with fleet size ranging from 1 to 8 vessels. The results are shown for three selected scenarios with respect to weather and time window duration. When weather effects are ignored, a fleet performance of 100% is achieved for a fleet of four vessels. In the two other scenarios weather conditions are challenging, and time windows of 9 and 3 days yields fleet performances of 96.6% and 82.2%, respectively, for a fleet size of eight. The gap between the lightest and darkest shade describes the effect of shorter, fewer, and coincident weather windows between the fish farms.

Discussion

The relevance of the presented method is based on the expansion of the sea-based fish farming industry into more exposed waters which both introduces more challenging weather conditions for vessel operations and an increased spread in simultaneous weather between fish farms, from sheltered to fully exposed locations. This expansion entails uncertainty about how well current solutions perform. Important questions cover if fish farms should

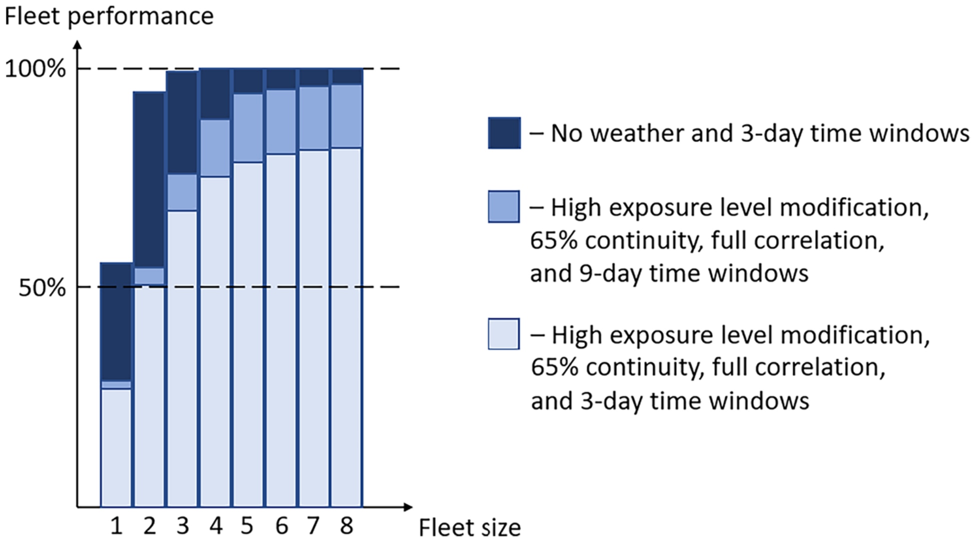


Fig. 11 Achieved fleet performance for different sized fleets of multi-purpose vessels. The results are presented for three selected weather scenarios, indicated by the different shades of color

be divided into groups based on exposure that are operated by dedicated fleets of vessels, if and what new technological solutions that are needed to enable operation at exposed locations, how to best compose fleets of service vessels to serve a number of fish farms experiencing very different weather, and if any other measures can be taken to improve fleet performance. A method enabling the assessment of fleet performance through scenario analysis is a valuable tool for getting answers to such questions and providing insight to support decision processes.

The presented method achieves this by performing short-term simulations of the operation of the fleet, including specific mission lists and weather time series and a flexibility in changing fleet composition and fish farms during the simulations. This means that all possible system configurations can be tested, and absolute fleet performance can be retrieved. However, for a given scenario the accuracy of the fleet performance depends on the match between the vessel routing method used in practice and the method applied in this paper. Perfect validity is achieved if the routing and scheduling in the method is the same as the one used for the real-world situation of the considered fleet, and if the considered weather scenarios and operation request are perfect representations of the behavior of the real system. The idea behind the chosen setup of the method is that comparing the maximum performance of the fleets is a valid approach for comparing fleet alternatives and that fish farmers seek optimal utilization of the vessels they operate. Most vessels in fish farming are either routed individually or not routed using optimization methods, meaning that the performance established by the method is likely to be higher than that of the real-case scenario. Scenario testing also complicates extreme event testing because it is not readily given what weather and mission list scenarios that give the lowest fleet performance, that is, establishing extreme event scenarios with respect to weather and mission lists may not give the “desired” extreme event scenarios for fleet performance.

The method for solving the operational sub-problems is based on the routing heuristic of Lianes et al. (2021), an Adaptive Large Neighborhood Search (ALNS) heuristic tailored for solving the problem of routing service vessels in sea-based fish farming considering several of the most important characteristics of the routing problem such as operational limits, time windows, functional requirements, heterogeneous fleets and prerequisites for performing operations. Configuring the method requires the selection of a range of parameters including the duration of the central and forecast period and parameters related to solving the sub-problem such as the number of search iterations, randomness in the search, and the profits and costs. Most parameters of the ALNS heuristic were kept unchanged compared to the configuration used in Lianes et al. (2021), except for the number of search iterations which was reduced to give a shorter computational time, and the profits and costs which were changed to simply maximize the number of completed operations. That is, all operations were given the same profit and all costs were set to zero. A sensitivity analysis was performed to investigate the reduction in solution quality from the implemented reduction in the number of search iterations, and it was found to be within a couple percent of the absolute performance and not affecting the ranking order of the experiments.

Weather scenarios and vessel characteristics are based on real data that are modified to perform the desired experiments. For the weather, this entails creating time series with somewhat exaggerated characteristics such as the full correlation, but that are well suited to demonstrate the direction and magnitude of effects from changes in weather scenarios. Even though the construction of the modified time series can be questioned, the resulting time series are judged reasonable and show the desired variation for the experiments. Only a limited number of experiments were performed, but they do provide a demonstration of the variations in fleet performance that can result from different weather scenarios. It should also be noted that only one parameter is used to represent weather, and even though significant wave height is often the main consideration with respect to operational limits for vessel operations (Det Norske Veritas AS 2011) , other parameters like wave period, wind, and current are also important (Sandvik et al., 2018; Shen et al., 2019b). Vessel characteristics are not extensively described in the method, only including sailing speed, what operations the vessels can perform, and operational limit. Having a common operational limit for the three operations and two vessel types does not necessarily decrease the validity of the experiments as there are several examples of this being the case in practice, either because many vessels have similar motion characteristics or because they have similar interactions with the fish farm.

Testing the fleet performance of two different fleets for a range of different weather scenarios is in line with the purpose of the method and provides insight on the potential effects of changes in weather scenarios on fleet performance. The tested weather scenarios are relevant for the expansion of the industry into more exposed locations, and the changes in time window length and the two fleet compositions cover a variation in fleet design and measures to improve fleet performance.

As expected, the results show that higher exposure level modification reduces the fleet performance and that the multi-purpose fleet performs better than the specialized fleet. The latter is supported by the higher utilization of the multi-purpose vessels because they, on average, need to sail shorter between operations when optimally routed, and they consequently achieve a superior utilization of the weather windows of the operations on a fleet level. Higher continuity and correlation both give reductions in fleet performance similar in magnitude to that of higher exposure levels, using the definition of the terms and the level values presented in this paper. Interestingly, the effects seem to follow the superposition principle, in terms of how the effects add to a total percentage reduction. Exposure level and continuity affects how often the locations are unavailable for vessel operations and for how long each time. Full correlation poses a challenge for locations where periods of rough weather are frequently expected, because it can lead to a spike in vessel operation demand as soon as the weather calms. As such, full correlation requires better operation planning to avoid a build-up of the vessel operation backlog, than for low or normal correlation where the availability of the locations is more evenly spread, which in turn reduces the peak demand. For high correlation, having a high peak demand in comparison to the capacity of the fleet of service vessels results in additional delays for vessel operations at fish farms after becoming available again after periods of rough weather. The largest difference in performance for a fleet in the case study is almost 50% between the least and most challenging weather scenarios, for the specialized fleet with three vessels.

Increasing the time window lengths and the number of vessels in the fleet both improves fleet performance, with the time windows determining the upper boundary the fleet performance approaches with increasing size (see the convergence in Fig. 11). The results therefore show that it is possible to serve a set of farms of different exposure with the same fleet of vessels and still achieve high fleet performance. Increasing the number of vessels, and the time window lengths can, in the case of the fleet of multi-purpose vessels, bring the performance back up close to 100%. However, 100% fleet performance requires additional measures such as higher operational limits, more vessels in the fleet, and designing fish farms and planning their operations so that it is not necessary to perform vessel operations in rough weather. The latter does not cover emergency operations which, by definition, cannot be planned for and must therefore be addressed through the other means.

Using the presented method to perform scenario analyses can improve decision making on vessel procurement and how to organize and deploy vessels based on the weather conditions at the locations. Scenario analysis can also be used operationally to study the effectivity of different response actions in shorter periods of challenging weather or testing possible operational changes for improvement of day-to-day operation. In addition, the method can provide insight on the effect of possible challenging situations or disrupting event and changes, and the effectivity of the available tools for dealing with such situations. Improved insight is likely to give higher fleet performance which in turn affects operation costs. Requested operations are usually necessary for the operation of the fish farms which means that the fish farmers desire a fleet performance of 100% and are interested in the most effective ways of approaching such high performance. The worst-case scenario is that insufficient fleet performance leads to operational difficulties at the fish farms, which in turn can result in reduced fish welfare and reduced profitability.

The results indicate that all considered parameter variations in the experiment setup do have significant effect on fleet performance and should therefore be assessed when composing service vessel fleets and determining what fish farms the various vessels serve. A main finding is that vessels should be organized so that they share responsibility of farms that are not fully correlated. It is also clear that higher exposure levels and higher continuity reduces performance. However, the fact that the industry is expanding to more exposed locations is mainly driven by the scarcity of sheltered locations, hence it is not a solution to avoid rough conditions all together.

This method opens for evaluating vessels' ability to cooperate, and how that is affected by different operating conditions, e.g., weather conditions and time windows. Significant reductions in performance, like what was seen in Fig. 10, would indicate a need to reevaluate the fleet composition. Considering actual time windows and operational limits, the fleet performance should ideally be close to 100% depending on the acceptable level of spot charter. Even though special purpose vessels are on the rise, decision makers should consider the value of procuring versatile vessel designs so that they can perform other operations if that is beneficial for the total performance. E.g., modular vessel designs.

Figure 11 shows that increasing the fleet size is not always a solution, which also means that improved sailing speed or operational durations do not solve the problem if weather windows are too few or coincident. Then, the only solution is higher operational limits.

With new farm concepts and new vessel designs being introduced, experience-based knowledge is less relevant and methods for objectively assessing complex relations are necessary.

Conclusion

This paper presents a method for assessing the performance of a fleet of aquaculture service vessels serving a set of fish farms at locations of varying exposure level under diverse weather conditions. The motivation is the expansion of sea-based fish farms into more exposed areas, and how this sets new requirements for vessel operations on the fleet level to support the fish farms. A case study demonstrates changes in fleet performance for different weather scenarios, fleet composition, and time windows for operations. Exposure level, continuity, and correlation, as defined in the paper, all have significant impact on fleet performance, giving a total reduction in performance of almost 50% in the most severe scenario in the case study. More vessels and longer time windows can, in the case of a fleet of multi-purpose vessels, bring the performance back up close to 100%. The studied locations cover existing fish farms, and with a future increase in the number of exposed locations and diversity in designs and technical solutions, the benefit of performing fleet performance assessments is likely to only increase. Scenario analyses can be a powerful tool for decision support both for short-term routing problems and long-term fleet composition and fish farm design.

Acknowledgements The authors would like to thank Professor Pål Furset Lader for providing the fetch length mappings for the locations 31557 Valøyan and 12348 Kåholmen.

Author contribution Conception and design were mainly the works of Hans Tobias Slette and Bjørn Egil Asbjørnslett. Material preparation, data collection, and analysis were performed by Hans Tobias Slette, Bjørn Egil Asbjørnslett, and Kjetil Fagerholt. The first draft of the manuscript was written by Hans Tobias Slette, and Bjørn Egil Asbjørnslett and Kjetil Fagerholt commented on previous versions of the manuscript. Ingeborg Margrete Lianes, Maren Theisen Noreng, and Hans Tobias Slette have developed new software used in the paper. All authors read and approved the final manuscript.

Funding Open access funding provided by NTNU Norwegian University of Science and Technology (incl St. Olavs Hospital - Trondheim University Hospital) This research has been funded by the Research Council Norway, EXPOSED Aquaculture Research Centre, grant number 237790. The funding source had no influence on the research or the preparation of the article.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability The code generated in the current study is available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Competing interests The authors declare no competing interests.

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Research paper 5

Susceptibility to weather induced delays in vessel operations at marine fish farms
Slette, H.T.; Lader, P.F.; Asbjørnslett, B.E.
Has been submitted to scientific journal

Appendix B: Previous PhD theses published at the Department of Marine Technology

Previous PhD theses published at the Department of Marine Technology (earlier: Faculty of Marine Technology)
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)

UR-79- x	Finn Gunnar Nielsen, MH	Hydrodynamic problems related to oil barriers for offshore application
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)

UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis

MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)
MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)

MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)
MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
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IMT-3-2015	Fredriksen, Arnt Gunvald	A numerical and experimental study of a two-dimensional body with moonpool in waves and current, CeSOS
IMT-4-2015	Jose Patricio Gallardo Canabes	Numerical studies of viscous flow around bluff bodies, IMT
IMT-5-2015	Vegard Longva	Formulation and application of finite element techniques for slender marine structures subjected to contact interactions, IMT
IMT-6-2015	Jacobus De Vaal	Aerodynamic modelling of floating wind turbines, CeSOS
IMT-7-2015	Fachri Nasution	Fatigue Performance of Copper Power Conductors, IMT
IMT-8-2015	Oleh I Karpa	Development of bivariate extreme value distributions for applications in marine technology,CeSOS
IMT-9-2015	Daniel de Almeida Fernandes	An output feedback motion control system for ROVs, AMOS
IMT-10-2015	Bo Zhao	Particle Filter for Fault Diagnosis: Application to Dynamic Positioning Vessel and Underwater Robotics, CeSOS
IMT-11-2015	Wenting Zhu	Impact of emission allocation in maritime transportation, IMT
IMT-12-2015	Amir Rasekhi Nejad	Dynamic Analysis and Design of Gearboxes in Offshore Wind Turbines in a Structural Reliability Perspective, CeSOS
IMT-13-2015	Arturo Jesùs Ortega Malca	Dynamic Response of Flexibles Risers due to Unsteady Slug Flow, CeSOS
IMT-14-2015	Dagfinn Husjord	Guidance and decision-support system for safe navigation of ships operating in close proximity, IMT
IMT-15-2015	Anirban Bhattacharyya	Ducted Propellers: Behaviour in Waves and Scale Effects, IMT
IMT-16-2015	Qin Zhang	Image Processing for Ice Parameter Identification in Ice Management, IMT
IMT-1-2016	Vincentius Rumawas	Human Factors in Ship Design and Operation: An Experiential Learning, IMT

IMT-2-2016	Martin Storheim	Structural response in ship-platform and ship-ice collisions, IMT
IMT-3-2016	Mia Abrahamsen Prsic	Numerical Simulations of the Flow around single and Tandem Circular Cylinders Close to a Plane Wall, IMT
IMT-4-2016	Tufan Arslan	Large-eddy simulations of cross-flow around ship sections, IMT
IMT-5-2016	Pierre Yves-Henry	Parametrisation of aquatic vegetation in hydraulic and coastal research,IMT
IMT-6-2016	Lin Li	Dynamic Analysis of the Instalation of Monopiles for Offshore Wind Turbines, CeSOS
IMT-7-2016	Øivind Kåre Kjerstad	Dynamic Positioning of Marine Vessels in Ice, IMT
IMT-8-2016	Xiaopeng Wu	Numerical Analysis of Anchor Handling and Fish Trawling Operations in a Safety Perspective, CeSOS
IMT-9-2016	Zhengshun Cheng	Integrated Dynamic Analysis of Floating Vertical Axis Wind Turbines, CeSOS
IMT-10-2016	Ling Wan	Experimental and Numerical Study of a Combined Offshore Wind and Wave Energy Converter Concept
IMT-11-2016	Wei Chai	Stochastic dynamic analysis and reliability evaluation of the roll motion for ships in random seas, CeSOS
IMT-12-2016	Øyvind Selnes Patricksson	Decision support for conceptual ship design with focus on a changing life cycle and future uncertainty, IMT
IMT-13-2016	Mats Jørgen Thorsen	Time domain analysis of vortex-induced vibrations, IMT
IMT-14-2016	Edgar McGuinness	Safety in the Norwegian Fishing Fleet – Analysis and measures for improvement, IMT
IMT-15-2016	Sepideh Jafarzadeh	Energy effiency and emission abatement in the fishing fleet, IMT
IMT-16-2016	Wilson Ivan Guachamin Acero	Assessment of marine operations for offshore wind turbine installation with emphasis on response-based operational limits, IMT

IMT-17-2016	Mauro Candeloro	Tools and Methods for Autonomous Operations on Seabed and Water Coumn using Underwater Vehicles, IMT
IMT-18-2016	Valentin Chabaud	Real-Time Hybrid Model Testing of Floating Wind Tubines, IMT
IMT-1-2017	Mohammad Saud Afzal	Three-dimensional streaming in a sea bed boundary layer
IMT-2-2017	Peng Li	A Theoretical and Experimental Study of Wave-induced Hydroelastic Response of a Circular Floating Collar
IMT-3-2017	Martin Bergström	A simulation-based design method for arctic maritime transport systems
IMT-4-2017	Bhushan Taskar	The effect of waves on marine propellers and propulsion
IMT-5-2017	Mohsen Bardestani	A two-dimensional numerical and experimental study of a floater with net and sinker tube in waves and current
IMT-6-2017	Fatemeh Hoseini Dadmarzi	Direct Numerical Simualtion of turbulent wakes behind different plate configurations
IMT-7-2017	Michel R. Miyazaki	Modeling and control of hybrid marine power plants
IMT-8-2017	Giri Rajasekhar Gunnu	Safety and effiency enhancement of anchor handling operations with particular emphasis on the stability of anchor handling vessels
IMT-9-2017	Kevin Koosup Yum	Transient Performance and Emissions of a Turbocharged Diesel Engine for Marine Power Plants
IMT-10-2017	Zhaolong Yu	Hydrodynamic and structural aspects of ship collisions
IMT-11-2017	Martin Hassel	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations
IMT-12-2017	Astrid H. Brodtkorb	Hybrid Control of Marine Vessels – Dynamic Positioning in Varying Conditions
IMT-13-2017	Kjersti Bruserud	Simultaneous stochastic model of waves and current for prediction of structural design loads

IMT-14-2017	Finn-Idar Grøtta Giske	Long-Term Extreme Response Analysis of Marine Structures Using Inverse Reliability Methods
IMT-15-2017	Stian Skjong	Modeling and Simulation of Maritime Systems and Operations for Virtual Prototyping using co-Simulations
IMT-1-2018	Yingguang Chu	Virtual Prototyping for Marine Crane Design and Operations
IMT-2-2018	Sergey Gavrilin	Validation of ship manoeuvring simulation models
IMT-3-2018	Jeevith Hegde	Tools and methods to manage risk in autonomous subsea inspection,maintenance and repair operations
IMT-4-2018	Ida M. Strand	Sea Loads on Closed Flexible Fish Cages
IMT-5-2018	Erlend Kvinge Jørgensen	Navigation and Control of Underwater Robotic Vehicles
IMT-6-2018	Bård Stovner	Aided Intertial Navigation of Underwater Vehicles
IMT-7-2018	Erlend Liavåg Grotle	Thermodynamic Response Enhanced by Sloshing in Marine LNG Fuel Tanks
IMT-8-2018	Børge Rokseth	Safety and Verification of Advanced Maritime Vessels
IMT-9-2018	Jan Vidar Ulveseter	Advances in Semi-Empirical Time Domain Modelling of Vortex-Induced Vibrations
IMT-10-2018	Chenyu Luan	Design and analysis for a steel braceless semi-submersible hull for supporting a 5-MW horizontal axis wind turbine
IMT-11-2018	Carl Fredrik Rehn	Ship Design under Uncertainty
IMT-12-2018	Øyvind Ødegård	Towards Autonomous Operations and Systems in Marine Archaeology
IMT-13-2018	Stein Melvær Nornes	Guidance and Control of Marine Robotics for Ocean Mapping and Monitoring

IMT-14-2018	Petter Norgren	Autonomous Underwater Vehicles in Arctic Marine Operations: Arctic marine research and ice monitoring
IMT-15-2018	Minjoo Choi	Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context
MT-16-2018	Ole Alexander Eidsvik	Dynamics of Remotely Operated Underwater Vehicle Systems
IMT-17-2018	Mahdi Ghane	Fault Diagnosis of Floating Wind Turbine Drivetrain- Methodologies and Applications
IMT-18-2018	Christoph Alexander Thieme	Risk Analysis and Modelling of Autonomous Marine Systems
IMT-19-2018	Yugao Shen	Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence
IMT-20-2018	Tianjiao Dai	Investigations of Shear Interaction and Stresses in Flexible Pipes and Umbilicals
IMT-21-2018	Sigurd Solheim Pettersen	Resilience by Latent Capabilities in Marine Systems
IMT-22-2018	Thomas Sauder	Fidelity of Cyber-physical Empirical Methods. Application to the Active Truncation of Slender Marine Structures
IMT-23-2018	Jan-Tore Horn	Statistical and Modelling Uncertainties in the Design of Offshore Wind Turbines
IMT-24-2018	Anna Swider	Data Mining Methods for the Analysis of Power Systems of Vessels
IMT-1-2019	Zhao He	Hydrodynamic study of a moored fish farming cage with fish influence
IMT-2-2019	Isar Ghamari	Numerical and Experimental Study on the Ship Parametric Roll Resonance and the Effect of Anti-Roll Tank

IMT-3-2019	Håkon Strandenes	Turbulent Flow Simulations at Higher Reynolds Numbers
IMT-4-2019	Siri Mariane Holen	Safety in Norwegian Fish Farming – Concepts and Methods for Improvement
IMT-5-2019	Ping Fu	Reliability Analysis of Wake-Induced Riser Collision
IMT-6-2019	Vladimir Krivopolianskii	Experimental Investigation of Injection and Combustion Processes in Marine Gas Engines using Constant Volume Rig
IMT-7-2019	Anna Maria Kozlowska	Hydrodynamic Loads on Marine Propellers Subject to Ventilation and out of Water Condition.
IMT-8-2019	Hans-Martin Heyn	Motion Sensing on Vessels Operating in Sea Ice: A Local Ice Monitoring System for Transit and Stationkeeping Operations under the Influence of Sea Ice
IMT-9-2019|	Stefan Vilsen	Method for Real-Time Hybrid Model Testing of Ocean Structures – Case on Slender Marine Systems
IMT-10-2019	Finn-Christian W. Hanssen	Non-Linear Wave-Body Interaction in Severe Waves
IMT-11-2019	Trygve Olav Fossum	Adaptive Sampling for Marine Robotics
IMT-12-2019	Jørgen Bremnes Nielsen	Modeling and Simulation for Design Evaluation
IMT-13-2019	Yuna Zhao	Numerical modelling and dyncamic analysis of offshore wind turbine blade installation
IMT-14-2019	Daniela Myland	Experimental and Theoretical Investigations on the Ship Resistance in Level Ice
IMT-15-2019	Zhengru Ren	Advanced control algorithms to support automated offshore wind turbine installation
IMT-16-2019	Drazen Polic	Ice-propeller impact analysis using an inverse propulsion machinery simulation approach

IMT-17-2019	Endre Sandvik	Sea passage scenario simulation for ship system performance evaluation
IMT-18-2019	Loup Suja-Thauvin	Response of Monopile Wind Turbines to Higher Order Wave Loads
IMT-19-2019	Emil Smilden	Structural control of offshore wind turbines – Increasing the role of control design in offshore wind farm development
IMT-20-2019	Aleksandar-Sasa Milakovic	On equivalent ice thickness and machine learning in ship ice transit simulations
IMT-1-2020	Amrit Shankar Verma	Modelling, Analysis and Response-based Operability Assessment of Offshore Wind Turbine Blade Installation with Emphasis on Impact Damages
IMT-2-2020	Bent Oddvar Arnesen Haugaløkken	Autonomous Technology for Inspection, Maintenance and Repair Operations in the Norwegian Aquaculture
IMT-3-2020	Seongpil Cho	Model-based fault detection and diagnosis of a blade pitch system in floating wind turbines
IMT-4-2020	Jose Jorge Garcia Agis	Effectiveness in Decision-Making in Ship Design under Uncertainty
IMT-5-2020	Thomas H. Viuff	Uncertainty Assessment of Wave-and Current-induced Global Response of Floating Bridges
IMT-6-2020	Fredrik Mentzoni	Hydrodynamic Loads on Complex Structures in the Wave Zone
IMT-7-2020	Senthuran Ravinthrakumar	Numerical and Experimental Studies of Resonant Flow in Moonpools in Operational Conditions
IMT-8-2020	Stian Skaalvik Sandøy	Acoustic-based Probabilistic Localization and Mapping using Unmanned Underwater Vehicles for Aquaculture Operations
IMT-9-2020	Kun Xu	Design and Analysis of Mooring System for Semi-submersible Floating Wind Turbine in Shallow Water
IMT-10-2020	Jianxun Zhu	Cavity Flows and Wake Behind an Elliptic Cylinder Translating Above the Wall
IMT-11-2020	Sandra Hogenboom	Decision-making within Dynamic Positioning Operations in the Offshore Industry – A Human Factors based Approach

IMT-12-2020	Woongshik Nam	Structural Resistance of Ship and Offshore Structures Exposed to the Risk of Brittle Failure
IMT-13-2020	Svenn Are Tutturen Værnø	Transient Performance in Dynamic Positioning of Ships: Investigation of Residual Load Models and Control Methods for Effective Compensation
IMT-14-2020	Mohd Atif Siddiqui	Experimental and Numerical Hydrodynamic Analysis of a Damaged Ship in Waves
IMT-15-2020	John Marius Hegseth	Efficient Modelling and Design Optimization of Large Floating Wind Turbines
IMT-16-2020	Asle Natskår	Reliability-based Assessment of Marine Operations with Emphasis on Sea Transport on Barges
IMT-17-2020	Shi Deng	Experimental and Numerical Study of Hydrodynamic Responses of a Twin-Tube Submerged Floating Tunnel Considering Vortex-Induced Vibration
IMT-18-2020	Jone Torsvik	Dynamic Analysis in Design and Operation of Large Floating Offshore Wind Turbine Drivetrains
IMT-1-2021	Ali Ebrahimi	Handling Complexity to Improve Ship Design Competitiveness
IMT-2-2021	Davide Proserpio	Isogeometric Phase-Field Methods for Modeling Fracture in Shell Structures
IMT-3-2021	Cai Tian	Numerical Studies of Viscous Flow Around Step Cylinders
IMT-4-2021	Farid Khazaeli Moghadam	Vibration-based Condition Monitoring of Large Offshore Wind Turbines in a Digital Twin Perspective
IMT-5-2021	Shuaishuai Wang	Design and Dynamic Analysis of a 10-MW Medium-Speed Drivetrain in Offshore Wind Turbines
IMT-6-2021	Sadi Tavakoli	Ship Propulsion Dynamics and Emissions
IMT-7-2021	Haoran Li	Nonlinear wave loads, and resulting global response statistics of a semi-submersible wind turbine platform with heave plates
IMT-8-2021	Einar Skiftestad Ueland	Load Control for Real-Time Hybrid Model Testing using Cable-Driven Parallel Robots

IMT-9-2021	Mengning Wu	Uncertainty of machine learning-based methods for wave forecast and its effect on installation of offshore wind turbines
IMT-10-2021	Xu Han	Onboard Tuning and Uncertainty Estimation of Vessel Seakeeping Model Parameters
IMT-01-2022	Ingunn Marie Holmen	Safety in Exposed Aquacultrue Operations
IMT-02-2022	Prateek Gupta	Ship Performance Monitoring using In-service Measurements and Big Data Analysis Methods
IMT-03-2022	Sangwoo Kim	Non-linear time domain analysis of deepwater riser vortex-induced vibrations
IMT-04-2022	Jarle Vinje Kramer	Hydrodynamic Aspects of Sail-Assisted Merchant Vessels
IMT-05-2022	Øyvind Rabliås	Numerical and Expermental Studies of Maneuvering in Regular and Irregular Waves
IMT-06-2022	Pramod Ghimire	Simulation-Based Ship Hybrid Power System Conspet Studies and Performance Analyses
IMT-07-2022	Carlos Eduardo Silva de Souza	Structural modelling, coupled dynamics, and design of large floating wind turbines
IMT-08-2022	Lorenzo Balestra	Design of hybrid fuel cell & battery systems for maritime vessels
IMT-09-2022	Sharmin Sultana	Process safety and risk management using system perspectives – A contribution to the chemical process and petroleum industry
IMT-10-2022	Øystein Sture	Autonomous Exploration for Marine Minerals
IMT-11-2022	Tiantian Zhu	Information and Decision-making for Major Accident Prevention – A concept of information-based strategies for accident prevention
IMT-12-2022	Siamak Karimi	Shore-to-Ship Charging Systems for Battery-Electric Ships
IMT-01-2023	Huili Xu	Fish-inspired Propulsion Study: Numerical Hydrodynamics of Rigid/Flexible/Morphing Foils and Observations on Real Fish
IMT-02-2023	Chana Sinsabvarodom	Probabilistic Modelling of Ice-drift and Ice Loading on Fixed and Floating Offshore Structures

IMT-03-2023	Martin Skaldebø	Intelligent low-cost solutions for underwater intervention using computer vision and machine learning
IMT-04-2023	Hans Tobias Slette	Vessel operations in exposed aquaculture – Achieving safe and efficient operation of vessel fleets in fish farm systems experiencing challenging metocean conditions