Master's thesis

NTNU
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Strategic Planning in Norwegian Aquaculture

A Decision-Support System for Fleet Size and Mix Problems with Processing Vessels

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
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Mats Wærøe Langseth

Strategic Planning in Norwegian Aquaculture
- A Decision-Support System for Fleet Size and Mix Problems with Processing Vessels

Background

New special vessels for salmon transport are being introduced to the Norwegian aquaculture industry in keeping with recent focus areas of biological safety, fish welfare and emission reductions. However, with common practice still deeming shipowners highly profitable, there is little incentive to invest in changing their ways of operations. Quantitative strategic planning is scarce in the industry, which further extends the entry barrier for new vessels. With an applicable and functional decision-support tool for strategic planning which evaluates emissions and fish welfare aspects as well as costs, shipowners can gain a better understanding of what factors impact the performance of the fleet and how optimizing the fleet size and mix can increase the value in operations.

Objective

The overall goal of this thesis is to present a method for deriving the optimal fleet size and mix for a shipowner in the aquaculture industry. This will be done by maximizing the stakeholders' perceived value based on their evaluations of multiple value factors, including costs, emissions and fish welfare. This involves breaking down these value factors into comparable units to be weighted according to how the involved stakeholders value them.

Tasks
The candidate is recommended to cover the following parts in the project thesis:

- Determine common practice of strategic planning and fleet design in the aquaculture industry
- Consider the recent focus areas in the industry and how they affect operations
- Quantify the stakeholders’ core value factors into functional performance parameters
- Derive the stakeholders' evaluation of the performance parameters to create weighting averages
- Propose a method for solving fleet size and mix problems by maximizing stakeholder value
- Design optimization models describing deterministic operating conditions using FICO Xpress
- Design simulation models describing stochastic operating conditions using MATLAB SimEvents
- Implement scenario planning into design decisions using Epoch-Era Analysis
- Verify and validate the decision-support system through a feasibility study
- Discuss strength and improvement potentials of the proposed approach
- Conclude and propose suggestions for further work

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General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:

Main supervisor: Bjørn Egil Asbjørnslett

Sub-supervisor: Hans Tobias Slette

Company contact:

Deadline: 01.07.2020

Summary

With decades of vast success for shipowners in the Norwegian aquaculture industry, there has so far not been a strong push to incorporate comprehensive strategic planning into long-term decision-making. However, the introduction of specialized vessels for specific parts of the salmon supply chain has caused the fleet size and mix problem to become increasingly complicated for shipowners. The more special vessels that are introduced, the more value shipowners are potentially giving up by neglecting thorough strategic planning.

On these grounds, this thesis presented a decision-support system for solving maritime fleet size and mix problems for shipowners in the aquaculture industry. The system is based on the collaboration of optimization and simulation tools, where the optimization model derives the optimal fleet size and mix and vessel routing for deterministic operating conditions using integer programming, and the simulation model evaluates the derived fleets in stochastic operating conditions.

The decision-support system considers both conventional well-boats and the more recent processing vessels. In keeping with recent focus areas in the industry, the proposed method derives the optimal fleet size and mix by maximizing the overall performance of the fleet, evaluating fish welfare impacts and emission output as well as costs. This involves deriving functional performance parameters based on the quantification of fish welfare impacts and emissions.

A literature review is performed, determining the state of the art within Norwegian aquaculture, considering the deployed vessels and common practice for strategic planning and fleet design. Further, the proposed method and the construction of the decision-support system is described, before the system is demonstrated and analyzed in a feasibility study. Finally, assumptions, shortcomings and the system's applicability are discussed and concluded.

The results of the feasibility study are promising, with realistic results being derived while limiting computational time. They prove the value of strategic planning, as the derived optimal fleets includes both well-boats and processing vessels for all tested cases, which is uncommon for fleets in the industry today. Further, the derived results highlight possible improvements and extensions applicable to the decision-support system. These include implementing routing heuristics to the simulation model to better account for the underlying tactical planning problem, and carrying out more extensive research on fish welfare impacts during specific operations and the overall value of fish welfare.

Sammendrag

Grunnet tiår med enorm suksess for redere i norsk havbruk har det enda ikke vært noen stor etterspørsel etter å inkorporere grundig strategisk planlegging i langsiktig beslutningstaking. Med introduksjonen av spesialfartøy rettet mot spesifikke deler av logistikkjeden, har flåteoptimering blitt enda mer komplekst for redere. Jo flere spesialfartøy som introduseres, jo mer potensiell verdi taper rederene på å neglisjere strategisk planlegging.

På dette grunnlaget, presenterer denne rapporten et beslutningsstøttesystem for løsing av flåteoptimeringsproblemer for redere i havbruksnæringen. Systemet benytter seg av samspillet mellom optimerings- og simuleringsverktøy, hvor optimeringsmodellen utleder optimal flåte og fartøysruting under deterministiske operasjonstilstander ved hjelp av heltallsprogrammering, og simuleringsmodellen evaluerer flåtene under stokastiske operasjonstilstander.

Beslutningsstøttesystemet vurderer både konvensjonelle brønnbåter og mer moderne bløggebåter. I tråd med aktuelle fokusområder i næringen, utarbeider den foreslåtte løsningsmetoden den optimale flåten ved å maksimere den overordnede prestasjonen basert på fiskevelferd, utslipp og kostnadsfunksjoner. Dette involverer utarbeidelsen av funskjonelle prestasjonsparametre basert på kvantifiseringen av fiskevelferd og utslipp.

Et litteratursøk blir utført for å kartlegge moderne praksis i havbruksnæringen når det kommer til bruk av fartøy, strategisk planlegging og flåtedesign. Videre blir løsningsmetoden og utarbeidelsen av beslutningsstøttesystemet beskrevet og testet gjennom eksperimenter basert på reelle scenarier. Til slutt blir antakelser, tilkortkommenheter og systemets anvendbarhet diskutert og konkludert.

Resultatene er lovende, med gode resultater anskaffet på begrenset beregningstid. De beviser også verdien av strategisk planlegging, da den optimale flåten inkluderer både brønnbåter og bløggebåter for alle de utarbeidede testscenarioene, noe som er uvanlig i dagens havbruksflåter. De setter også lys på mulige utbedringer og anvendbare utvidelser av beslutningsstøttesystemet. Disse inkluderer implemetasjonen av en rutingsheuristikk i simuleringsmodellen for å bedre ta høyde for det underliggende taktiske planleggingproblemet, og forskning på den konkrete effekten av havbruksoperasjoner på fiskevelferd samt den overordnede verdien av fiskevelferd.

Preface

This thesis constitutes the complete workload of the course TMR4930 - Marine Technology, Master's Thesis, at the Norwegian University of Science and Technology (NTNU). The work done was conducted in the spring of 2020, and presents the last efforts of a five-year master's degree.

The main contribution of the work comprises of a decision-support system applying a proposed method of optimizing fleet performance by considering other value aspects than only costs for the Norwegian aquaculture industry.

The conducted work done has been highly demanding, but constructing a decision-support system from scratch based on a self-made method for holistically evaluating fleet performance based on recent focus areas in the aquaculture industry has been very rewarding.

I would like to express my deepest gratitude towards my supervisor, Professor Bjørn Egil Asbjørnslett at the Department of Marine Technology, NTNU, who has contributed with expert knowledge into the aquaculture industry, fleet design, and strategic problem solving. Furthermore, my gratitude extends to my co-supervisor, Hans Tobias Slette, who has provided knowledge of decision-support systems and modelling techniques.

Mats Wærøe Langseth

Trondheim, July 1, 2020

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Nomenclature

AHP Analytical Hierarchy Process

CAPEX Capital expenditures

CR Consistency Ratio

CRF Capital recovery factor

DBO Optimal fleet of both vessel types in deterministic conditions

DWO Optimal fleet of well-boats in deterministic conditions

EEA Epoch-Era Analysis

EEAO Optimal solution from the Epoch-Era Analysis

LNG Liquefied natural gas

LPG Liquefied petroleum gas

MAB Maximum allowable biomass

MDO Marine diesel oil

MUSD Million United States dollars

OPEX Operational expenditures

PD Pancreas disease

SBO Optimal fleet of both vessel types in stochastic conditions

SFC Specific fuel consumption

SWO Optimal fleet of well-boats in stochastic conditions

VOYEX Voyage-related expenditures

Chapter 1

Introduction

1.1 Background

Salmon aquaculture is a billion-dollar industry worldwide and is steadily expanding. A modernizing industry with a vast capital is now turning to new technology in keeping with recent focus areas. As the forerunner of salmon aquaculture worldwide, Norway is experiencing an increasing focus on fish welfare and biological safety in aquaculture. The transport of adult salmon is a critical part of the supply chain when it comes to securing the salmon's welfare and containing possible diseases. Experts are pointing to well-boats as problem-makers within this area and are calling for safer and more humane transport solutions[20, 26, 60]. Today's most common solution involves the slaughter-ready salmon being crowded and pumped into a well on board a well-boat, where they are kept alive during transport to the slaughterhouse. The transport is typically done largely with open compartments where water exchange happens naturally during sailing. A discussed predicament is contamination, both to the environment from salmon that may be infected by diseases and to the healthy salmon from the water inflow[60]. There is also a threat of disease spreading between the salmon inside the well. Recent technological advances has made well-boats able to transport salmon semi-closed (sometimes open, sometimes closed), but this only partly solves the problem as the salmon is dependent on continuously being supplied with oxygen from the fresh inflow of new water to the well[16]. Upon arrival at the slaughterhouse, the salmon is pumped into sea cages where they de-stress, typically for a few days, before being slaughtered. The crowding and pumping processes, both at the sea cages and at the slaughterhouse, increases the salmon's stress levels, which affects the fish welfare and can cause fatalities and physical damages[1, 27].

Introducing a more sensitive and risk-averting way of salmon transport has been discussed at lengths during the last decades, both to improve fish welfare and to increase biological security. Processing vessels were introduced to the Norwegian aquaculture industry in 2008 as an attempt to solve this problem. The processing vessels kill the salmon at the sea cages immediately after pumping them onboard. Thereafter, the dead salmon is kept in refrigerated seawater tanks (RSW-tanks) during transport to the slaughterhouse. As the salmon is already dead, fish welfare is not of any concern during transportation. Furthermore, the salmon is kept in closed tanks, meaning that biological safety is ensured.

Another focus area in seaborne transport that has been emphasized during the last decades is greenhouse emissions. The aquaculture industry accounts for a substantial part of the activity on the Norwegian continental shelf, and reducing emissions in the industry would help reduce the national output of greenhouse gases from seaborne transport. Since the processing vessels can contain salmon in a less space-demanding manner, i.e. without a large well filled with water, it can be smaller in size, and consequently the necessary power output and emissions are reduced during transport and operations.

Slaughter vessels have also been advocated, and have especially been gaining attention since the introduction of "Norwegian Gannet" in 2017. Instead of transporting the fish to a slaughterhouse, the slaughter vessels slaughter the fish entirely onboard before transporting the salmon to a processing facility abroad[56]. Replacing the lengthy land-based transport by trucks from the slaughterhouses to the processing facilities reduces both the emissions during transport and the impact on roads. As for processing vessels, the concern for fish welfare and biological safety on a slaughter vessel is recognized to a larger extent than for well-boats. A visualization of the discussed transport methods is given in Figure 1.1.

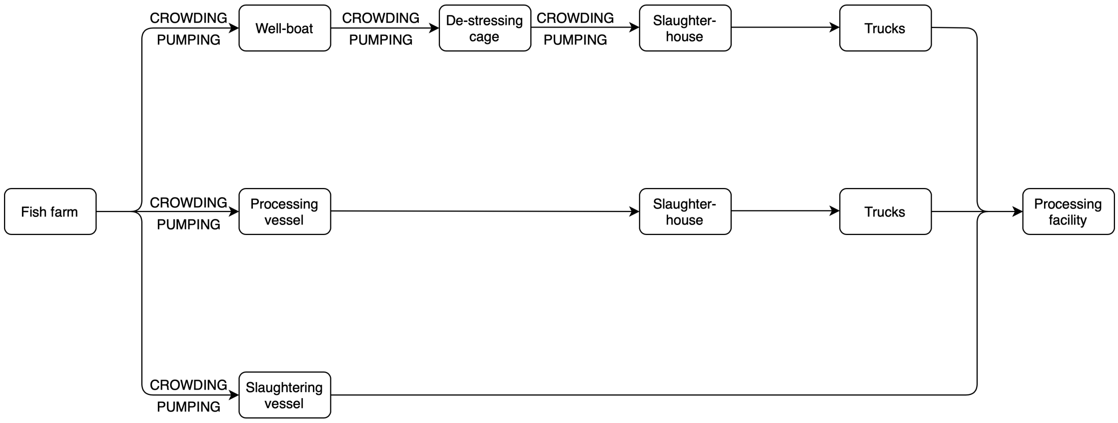

Figure 1.1: Flow chart of transport methods from the fish farm to the processing facility.

Today, transport of salmon is done almost exclusively by well-boats[60]. However, with the introduction of specialized vessels for salmon transport, some actors are starting to consider their options. Norway's largest salmon producer, Mowi, is among the companies that have invested in processing vessels. Their main incentive is biological safety and minimizing the risks of damaging their valuable cargo during crowding, pumping and transport[65]. The overall excitement surrounding the introduction of processing vessels have, however, been mild and there are only a few shipowners in the industry that have included these vessels in their fleets.

The introduction of slaughter vessels brought huge excitement in the industry, but the forerunner, the *Norwegian Gannet*, is still fighting a long-fought battle with the Norwegian Ministry of Trade, Industry and Fisheries on its right to operate. Norwegian legislation states that one cannot transport fish with open wounds or malformations abroad, which will regularly be part of the cargo when transporting large quantities of salmon directly abroad[46]. This has brought investments and interest in newbuilds to a pause, but alternative solutions to operating with slaughter vessels are now being considered, including transporting the salmon to processing facilities nationally rather than abroad to comply with regulations.

Although the specialized vessels pose solutions to some of the predicaments facing the industry, there is still an overall reluctance from shipowners in investing in these vessels. This is largely due to the interruption that these vessels would bring to the supply chain. The supply chain of the Norwegian aquaculture industry using well-boats is firmly established, and this practice has deemed shipowners highly profitable for decades. The well-boats are utilized for carrying out additional operations, like delousing and juvenile transport, which the vessels specialized for salmon transport cannot do. This implies that making a shift to specialized vessels for salmon transport, would require logistical restructures to still carry out all necessary operations as well as new contract negotiations with fish farmers and slaughterhouses. Further, the lack of extensive strategic planning in the industry poses a large entry barrier for processing and slaughter vessels. Shipowners that are satisfied with their current operations and that do not have applicable quantitative tools to evaluate whether they actually could be doing much better with different solutions, are typically unlikely to change their ways of operating.

With the introduction of special vessels complicating strategic decision-making further, applying decision-support tools could prove beneficial for the shipowners in optimizing the size and mix of their fleet and understanding the underlying routing problems necessary to optimize day-to-day operations. In keeping with the increased focus on operational aspects surpassing cost evaluations, e.g. fish welfare aspects, biological safety and emissions, a decision-support tool that evaluates fleet performance in a more holistic manner would be relevant. This way, the fleet could be optimized with regards to its overall performance regarding multiple value factors, rather than only minimizing costs.

1.2 Goals and Contributions

The overall goal of this thesis is to design a decision-support system and present a method for deriving the optimal fleet size and mix for a shipowner in the aquaculture industry. This will be done by maximizing the stakeholders' perceived value based on their evaluations of multiple value factors, including costs, emissions and fish welfare. This involves breaking down these value factors into comparable units to be weighted according to how the involved stakeholders value them. The list of contributions is given below.

- Determine common practice of strategic planning and fleet design in aquaculture
- Quantify the stakeholders core value factors into functional performance parameters
- Derive the stakeholders' evaluation of the performance parameters
- Propose a method for solving maritime fleet size and mix problems
- Design optimization models for deterministic operating conditions using FICO Xpress
- Design simulation models for stochastic operating conditions using MATLAB SimEvents
- Implement scenario planning into design decisions using Epoch-Era Analysis
- Verify and validate the decision-support system through a feasibility study

1.3 Limitations

As previously stated, shipowners in the Norwegian aquaculture industry have been reluctant in investing in specialized vessels for salmon transport. The processing vessels pose the smallest impact on the supply chain, where slaughterhouses still are involved and well-boats could be deployed together with processing vessels to carry out other required operations. Deploying slaughter vessels, would however result in a larger reconstruction of the supply chain, excluding the slaughterhouses and the truck transport. Furthermore, if the fleet is to supply multiple fish farms, the lengthy transport for slaughter vessels could imply that a large amount of vessels would be necessary to keep up with the desired frequency of pick-ups at the fish farms. It is also less practical to include slaughter vessels along with other vessels that also transport adult salmon, as this would require contracts with slaughterhouses and land-based transport companies, but only on a smaller quantity of the farmed salmon. By these arguments, slaughter vessels are considered to have little practical importance in a fleet size and mix problem in today's industry. Therefore, the proposed method will be limited to involving the deployment of well-boats and processing vessels. An illustration of the system boundary can be seen in Figure 1.2.

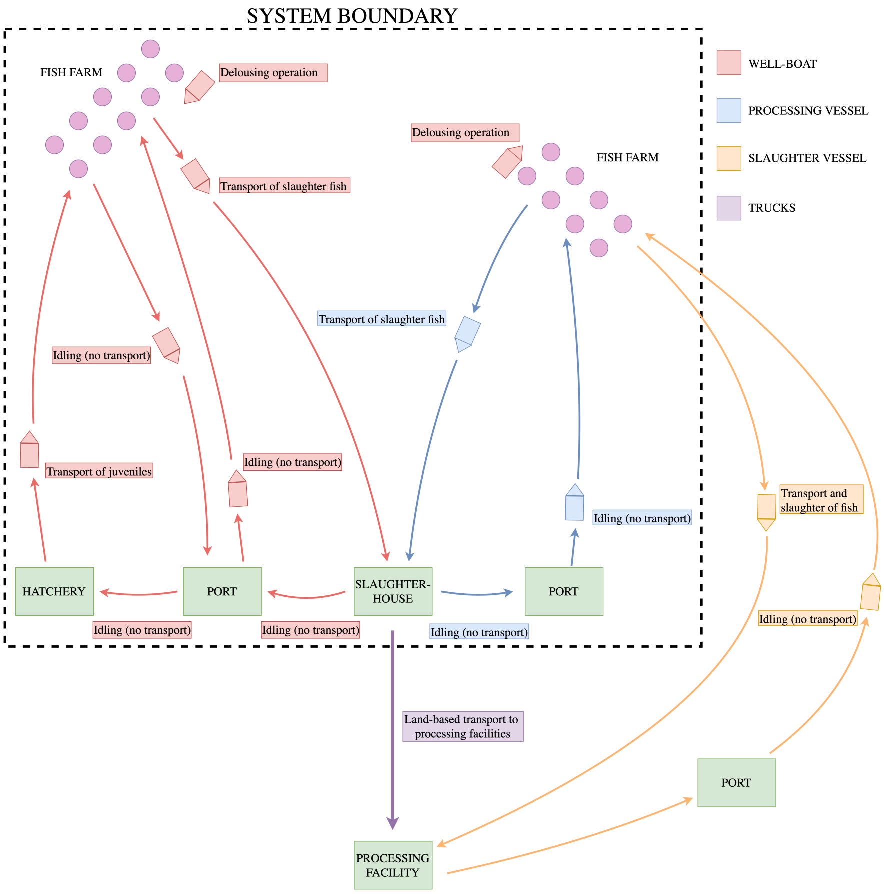

Figure 1.2: System boundary for this thesis

The remainder of this report is organized as follows: Chapter 2 is a literature review that describes the status of the Norwegian aquaculture industry as well as the vessel types used for salmon transport. It also presents common practice and covers planning approaches and fleet design methods commonly used in the maritime industry. Chapter 3 gives insight into the proposed method of this thesis and the construction of the decision-support system. It also presents the proposed performance parameters and a stakeholder analysis, before discussing the value of scenario planning. Next, the decision-support system is verified in a feasibility study presented in Chapter 4. Further, the proposed method's applications are discussed in Chapter 5, as well as commenting on the method's validity based on the assumptions made. Finally, concluding remarks are given in Chapter 6.

Chapter 2

Literature Review

In this section the state of the art of the Norwegian aquaculture industry will be presented. Common practice within salmon transport, strategic planning and fleet design will be derived and the potential for improvements will be discussed.

2.1 Norwegian Salmon Aquaculture

Salmon aquaculture has in just half a century gone from being a highly experimental "hobby pursuit" to becoming Norway's second most profitable industry, only beaten by the oil and gas industry. The aquaculture industry experienced exceptional growth for many decades but has in the last decade stagnated somewhat due to diseases becoming a more pressing problem. To prevent inimical farming tendencies and exhaustion of natural resources and available space on the continental shelf, the Norwegian government decided that one would not be granted additional licenses to expand farming activities unless the outbreak of diseases, especially sea-lice, was limited. As one can see in Figure 2.1, this has contributed to a stagnation in the exported quantity, although the value of the exported salmon has continued to increase.

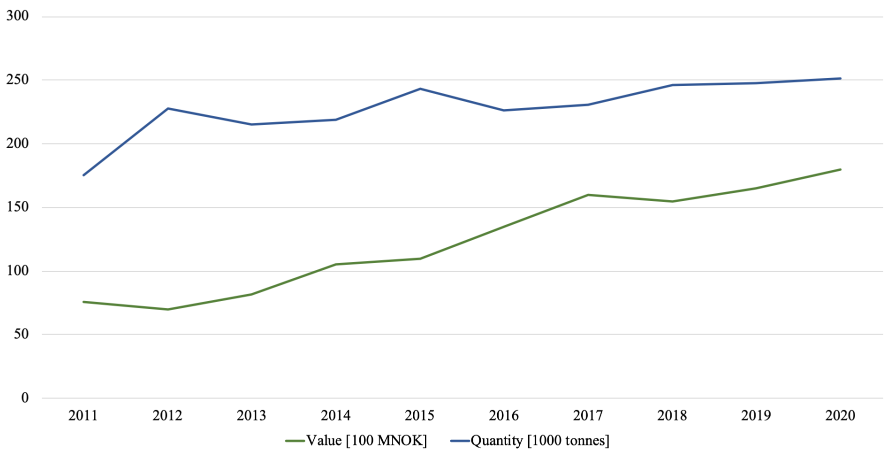

Figure 2.1: Norwegian Export of Salmon 2011-2020[44]

Value creation from Norwegian aquaculture has been forecasted to become even more substantial in the coming years. In 2012, a work group appointed by the Royal Norwegian Society of Sciences and Letters and the Norwegian Academy of Technological Sciences consisting of scientists from acknowledged research entities like SINTEF predicted that there would be a fivefold increase in value creation from Norwegian aquaculture and fisheries in 2050[47]. This prediction was based on the presumption that the industry would be victorious in combating sea-lice and other pressing diseases that affect the potential for expansion. Although the industry has been unable to expand as vastly as predicted in the past decade, the work highlights that the potential in Norwegian aquaculture is significant and that the industry should continue to be valuable for Norway's economic growth for many years to come.

The salmon production cycle is usually a three-year process, where the first 18 months are spent onshore and the following 18 months are spent at sea. Full-grown salmon is then transported to the slaughterhouses where they are killed, gutted and cut into fillets or stays as whole fish. Further, the Norwegian salmon is transported by trucks to processing facilities, typically in Poland or Denmark, where the salmon is processed so that it is ready to be sent directly to grocery stores and restaurants.

The transport of adult salmon from fish farms to the slaughterhouses is a small but vital part of the supply chain. Transporting the salmon means first crowding and pumping the salmon into the vessel. These operations are often fateful for a proportion of the salmon, as it strongly increases their stress levels and induces reactions that may cause them to harm themselves or others[27]. The three-year period of breeding the salmon is worthless if they harm themselves during crowding or pumping to the extent that the end-product cannot be sold as a high-quality product. There is little, or no literature considering the injury or mortality rates of the transport operations alone, but reports state that these operations account for a significant part of the overall threat facing farmed salmon[37].

The production costs of salmon farming increased sharply between 2012 and 2017, and is still at a high level[5]. This increase was mainly due to the costly and increasingly extensive disease treatments in salmon aquaculture. With a large production cost, it is more important than ever to ensure the salmon's safety in the final parts of the value chain to maintain profitability.

2.2 Vessels for Salmon Transport

As previously introduced, the well-boats and processing vessels are currently fighting for a single part of the salmon supply chain. Both vessels have clear strengths that make them strong options and shortcomings that make investors interested in keeping track of other alternatives. These vessel characteristics will be discussed in the following.

2.2.1 Well-Boats

Salmon transport by well-boat is done by first crowding the salmon in the fish cage and then pumping them into a large well filled with seawater on board the well-boat. As the salmon is dependent on some water flow movement to stay alive, the water inside the well is circulating continuously. To prevent hypoxia, there is steady water exchange throughout the transport. When the well-boat arrives at the slaughterhouse, the salmon is again pumped from the well-boat into local sea cages where they de-stress, usually for a couple of days. Finally, the salmon is crowded and pumped a third time into the slaughterhouse. Recent studies are now declaring the crowding and pumping operations as particularly harmful to the salmon, and the fact that modern well-boat transport requires three repetitions of these operations are being criticized[27, 37]. Furthermore, sailing lengthy distances with free water exchange between the well-boat and the surrounding waters is considered to bring an unnecessary risk of spreading diseases. In recent years, the occurrence of Pancreas Disease (PD) has become frequent in salmon aquaculture[29]. This has contributed to even larger concerns for salmon transport with open-compartments. Further, PD severely weakens the salmon's ability to withstand other hardship, like crowding, pumping and delousing operations.

In addition to transport operations, well-boats perform delousing operations and sorting operations. Delousing operations have proved to be vital for limiting the number of sea-lice affecting the salmon. National regulations state that one can only have 0.5 adult female sea-lice per salmon on average in a sea cage, and that if the number of sea-lice surpasses this, the entire sea cage biomass must be delivered for slaughter. Delivering 200.000 salmon per cage to slaughter prior to them being full-grown brings massive economical repercussions. This is why delousing operations are still a strong priority for aquaculture companies despite them being costly and harsh on the salmon[60].

The growth rate of each salmon is unique, meaning that if one places a school of juvenile salmon in a cage, they will not all be of the same size after a given period of time. Fish farmers may then want to sort the salmon over different cages in order to be able to make sure that all the salmon is being fed properly, i.e. the larger ones are not eating all the feed in the cage, or to balance out the salmon biomass between the cages to stay within the bounds set by the salmon licenses. Both delousing and sorting operations require crowding and pumping the fish, so many fish farmers decide to do sorting operations as an extension of delousing operations, meaning that one also carries out sorting when the well-boat is present to do delousing operations.

According to the Norwegian Well-Boat Owners Association, about 60% of the operations carried out by well-boats are transport missions of adult salmon to slaughterhouses, while about 30% are delousing operations and the remaining 10% are transport missions of juveniles[38]. Juvenile transport is typically done during the first few weeks of the sea-based production period, while delousing operations are done regularly, typically on a weekly basis, from the first week until the end of the production cycle. Transport operations of adult salmon may be done continuously for about half a year for a single fish farm. This is due to the fish farmers' exploitation of the maximum allowed biomass (MAB) on their salmon licenses. The MAB denotes the weight of live salmon a fish farmer can breed on one license at any given time, but does not govern over the total delivered biomass[33]. Therefore, as the salmon has unique growth rates, the fish farmers can deliver the first full-grown salmon as soon as the total biomass reaches the MAB, thus lowering the total biomass. This tactic of continuous deliveries is used throughout the production cycle, and typically results in a standard license with a MAB of 780 tonnes being turned into a delivered quantity of about 1000 tonnes[33].

A fish farm cluster usually consists of between 4 and 12 fish cages, and a single fleet of well-boats services a number of fish farm clusters at the same time. With the fish farms' production cycles rarely being aligned, a fleet of well-boats may carry out juvenile transport at one location, delousing operations at a second location, and adult salmon transport at a third location, all on the same day.

2.2.2 Processing Vessels

Processing vessels were first introduced to the European aquaculture industry in 2008, when the Norwegian shipowner Napier reconstructed their well-boat “Tauranga” into a vessel that could kill the salmon directly at the fish cages. Napier signed a contract with Marine Harvest (now Mowi) for Tauranga in 2009, and since, processing vessels have been gaining interest in the industry. As briefly described earlier, processing vessels differ from well-boats by killing the salmon, nowadays by so-called stun-and-bleed technology, before storing the dead salmon in refrigerated seawater tanks during transport. Sailing with dead salmon in closed compartments ensures biological safety and removes the issue of fish welfare effects during transport and delivery to slaughterhouses.

The processing vessels have a less space-demanding storage technique for the salmon, meaning that their size may be smaller whilst transporting the same amount of cargo. This contributes to limiting fuel output which keeps emissions low and fuel costs limited. Further, the physical impact on the fish cage structures during operations in rough weather is relatively smaller than for well-boats. Another benefit of processing vessels is that they can perform ”fish-saving” operations. The need for these operations can occur if there is an outbreak of disease at a fish farm and a portion of the cage is likely to die. The processing vessel then pumps the weakened salmon onboard and kills the salmon directly before transporting them to the slaughterhouse. The salmon may be so weak that they even die just from the pumping operation. This, however, ”saves” the end product of the salmon, as the end-product can still be delivered at a high quality. The well-boats are not able to do this. They cannot store the dead salmon in refrigerated tanks, which is necessary to maintain the quality.

While outshining well-boats when it comes to both fish welfare aspects and emissions, the processing vessels typically have a larger investment cost. In addition, the processing vessels have some distinct logistical shortcomings. As they cannot perform operations like juvenile transport and delousing, deploying processing vessels alone would require finding alternative solutions to performing these operations. As there are no specialized vessels for juvenile transport and delousing operations like the processing vessels are to salmon transport, deploying processing vessels still usually requires contributions from conventional well-boats.

2.3 Common Practice - Contracts

In order to make a decision support system for a fleet size and mix problem, it is important to understand what parties have an interest in this problem and what aspects should be impactful. The collaboration between the shipowner, who orders and operates the fleet, and the aquaculture company, who hires the fleet for missions, is especially important. The stakeholder analysis in Section 3.3 describes that there are additional stakeholders that have an interest in the design decisions, but the shipowner and the aquaculture companies have a special co-dependence that will be discussed in this section.

The shipowner’s overall goal is to win contracts to create profitable operations for its fleet. Oppositely, the aquaculture companies’ overall goal is to agree on a contract where all their required missions are carried out while maximizing their prospected value. Where formerly, the aquaculture companies and other stakeholders may have desired to only minimize their costs, recent focus areas are now demanding high performance within other operational aspects, meaning that the stakeholders may desire to maximize their perceived value based on multiple performance parameters.

There are three possible contract types that are typically agreed upon between the shipowner and the aquaculture companies: time charter, volume charter, and spot contracts[64]. Time charter is the most common contract type and typically include a given set of missions to be carried out on a weekly or monthly basis. There could be some alterations of the missions along the way, typically based on the occurrence of diseases or other stochastic influences, but these aspects typically do not affect the contracts. Time charter contracts are signed for a given amount of time, typically 4-7 years[64]. The contract length is important to the shipowner, as the shipowner must plan for missions for the entire lifetime of the fleet rather than focus solely on single contracts. However, if the agreed-upon contract is satisfactory for all parties, the missions have been carried out to a gratifying extent, and the fleet still complies with the aquaculture company's needs, contract extensions are natural. As a contract may originally span over just a fraction of the fleets lifetime, it is important for the fleet to be robust and flexible so that it can adapt to multiple possible future scenarios. Time charter contracts reduces the financial risk for shipowners as it gives a clear insight into future income and expenses, while it also reduces the operational risk for the aquaculture company as it ensures mission coverage throughout the contract period.

2.4 Planning and its Applications

The act of planning denotes the process of making plans to achieve a desired goal. In business, there are typically three discussed types of planning or planning levels: strategic, tactical and operational. Strategic planning is long-term, defining an overall strategy or direction. Tactical planning is short-term, emphasizing current operations. Operational planning describes the day-to-day decisions made during operations. In the maritime industry, a strategic planning problem may be a fleet size and mix problem or a market selection. A tactical planning problem may be the routing of vessels for a set of contracted missions and an operational planning problem may be the choice of service speed during a sailing leg[12].

Strategic planning is more common in some maritime industries than other. The shipping industry is among the industries where strategic planning is more common. Especially in deep-sea transport, where the sailing distances are long and contracts often are long-term or based on spot markets, both strategic and tactical planning can be very beneficial. Common approaches to solving strategic or tactical planning problems very often include optimization-based models like mixed-integer programming models, e.g. in [13]. These are functional on their own for small problems, but when considering larger problems, which strategic planning problems typically are, they become very time-consuming. Therefore, this method often relies on either disregarding some of the inherent tactical planning or using heuristics, and ultimately only deriving optimal solutions for small parts of the problem. Furthermore, optimization-based models are usually not able represent stochasticity very well. Some methods apply historic data to predict how various scenarios may look like, but this data does not necessarily represent future scenarios accurately[14].

Since there is such a strong interplay between strategic, tactical and operational planning levels in maritime planning problems, one cannot deliver efficient decision support on a strategic level without considering the underlying routing problem[14]. The routing and operational decisions are reliant on the current operational environment (missions, weather conditions, etc.). These variables are prone to high uncertainty, meaning that one week some missions may be relevant while the next week some different missions may be relevant and the weather conditions may vary a lot from day to day. Therefore, it is useful to consider not only what the optimal fleet size and mix for the static, deterministic problem is, but also how the dynamics and the stochasticity affects the inherent routing and operational planning problems[14].

A method that is able to represent stochasticity to a much larger degree is the application of simulation models. Using simulation tools alone is often time-consuming, and for strategic problems, one often has to omit the entire inherent tactical problem to bode for this. This may be problematic, as one is then unable to evaluate the effect of the tactical problem on the strategic problem. However, applying simulation tools along with optimization-based models may prove to be effective for solving large strategic problems. This combined approach has been widely discussed and applied in the literature[2, 4, 19, 49, 61]. The main challenge with this method is to handle the transition from one model to the next, e.g. from the optimization model to the simulation model, and ensure that the derived variables and parameters from one model actually provide valuable information to the other.

In the aquaculture industry, the most common approach for solving strategic problems are manual methods, sometimes supported by basic spreadsheet calculations[14]. The decision-makers are often people with long experience from the industry that trust their instincts and base their decisions on what they have found to be successful in the past[14]. Quantitative decision support models are only rarely used for strategic planning although they could provide large benefits regarding both maximizing value and increasing the fleets flexibility[14].

2.5 Fleet Design

Fleet design, i.e. designing an entire fleet, is not commonly done in the aquaculture industry. Fleet enhancement has been carried out by vessel design for a vessel to be added to the current fleet rather than a complete fleet renewal. New companies also often start out small with a few vessels before adding vessels to their fleet. In practice, companies often continuously add vessels to their fleet to have a somewhat diverse age on their fleet, so that one can purchase a new vessel when an old one is taken out of operation rather than doing complete fleet renewals.

The design problem at fleet level is far more complex than vessel design, as the interaction between vessels becomes a core focal point. Performance analysis on fleet level has to a larger extent been discussed in the literature, especially for emergency preparedness analyses. These analyses focus on fleet effectiveness, i.e. evaluating the fleet's degree of success in producing a desired result. Common methods include mixed integer programming and other optimization and simulation based approaches[6, 8, 23, 48, 67].

Although fleet renewal methods are not plentiful, two principal approaches are described in the following.

2.5.1 Tradespace Exploration

Tradespace exploration is a much discussed method for vessel design that is slowly being included as a method for fleet design, i.e. in [50]. This method is based on evolving the design space into a so-called tradespace, where the vessel or fleet designs typically are plotted based on cost and utility[52]. Utility play the same role as the stakeholder value and is a way of describing the performance within some given attributes. The term "tradespace" is derived from the design space being evolved into a space of trade-offs, e.g., how much are the stakeholders willing to invest to improve some value-adding attribute. The multi-attribute tradespace exploration is the most relevant for fleet design and is based on a weighting of multiple attributes towards a total utility value. Tradespace plots are typically made for different attributes and are often multi-dimensional, e.g., plotting cargo capacity against speed and investment costs. This is an effective way of increasing the understanding of trade-offs in the design decisions and to see what designs are dominated, meaning that there are other designs that fulfil the expectations to a larger degree at the same cost.

Tradespace exploration as a set-based design method, evaluates a larger number of possible designs for a longer time rather than settling on a strong design early on. This approach delays cost commitments, which may be effective, e.g., if there are many significantly different designs that all are strong contenders for being the best solution. The method often has a value-driven perspective that to a large extent focuses on the changing needs and expectations of the stakeholder. The method also links up well with the Epoch-Era Analysis (EEA), although the EEA also is effective combined with other design approaches. This will be discussed further in Section 3.5. On the downside, tradespace exploration has proved to be more problematic for multiple stakeholders with different preferences[3, 22] and is, as of yet, much more common for design problems at vessel level.

2.5.2 Optimization and Simulation-Based Approaches

Optimization and simulation-based approaches are the most common in fleet design. As previously discussed, optimization and simulation both have applications where they are effective, and they each have significant shortcomings when it comes to strategic planning in stochastic operating conditions. Therefore, these approaches are now being used together to take advantage of their strengths and limit their shortcomings. With the complexity of large strategic problems, optimization and simulation-based methods are often more efficient than other proposed method, which typically is the main reason for preferring this over other methods.

Chapter 3

Method

3.1 Approach

As previously stated, the overall goal of this work is to derive the optimal fleet size and mix for aquaculture operations with well-boats and processing vessels by maximizing the stakeholder value. Maximizing stakeholder value is done by fulfilling the goals and needs relevant to the operations. As well as the fleet carrying out all its missions, needs are met by performing well within the stakeholders' core value factors. These value factors are represented by performance parameters, which are measurable parameters affected by the design choices made for the fleet. These performance parameters will be defined and discussed in Section 3.2.

The overall performance of the fleet is based on its performance within the different performance parameters as well as the stakeholders' evaluation of each parameter. The stakeholders may decide that one performance parameter is more important than the other, and if so, this parameter would consequently be weighted heavier than the others in order to reflect the stakeholders' actual interests. Deriving the stakeholder needs and expectations is done by a stakeholder analysis in Section 3.3.

Fleet analysis is to be carried out by optimization and simulation models. Firstly, the optimal fleet for a given case assuming deterministic and static operating conditions is derived through an optimization model. Next, the fleet is evaluated in stochastic and dynamic operating conditions in a simulation model. The merit of alternative approaches will also be discussed. The stepwise process of deriving the optimal fleet and the model constructions are discussed in Section 3.4.

Finally, possible future scenarios that directly affect the operating environment are evaluated in a scenario planning process. These scenarios could include an increase in demand, an industry expansion to locations offshore and much more. The aim of this analysis is to evaluate the robustness of the fleets under future uncertainty. This is discussed in Section 3.5.

3.2 Performance Parameters

In order to be able to holistically grasp what the stakeholders value, functional performance parameters must be established. Performance parameters in this sense is the measurable representation of the stakeholders' core values. To be able to grasp the meaning of these parameters, it is vital that they are quantifiable and that the impacts on the parameters are measurable.

In salmon transport operations, stakeholder's typically have three core interests. Fish welfare, emissions and costs. Fish welfare is important both for securing the valuable end product and for gaining a strong reputation from exigent customers[42]. Emissions have gained strong attention in the maritime sector in the last decades, and especially vessels operating in the aquaculture industry, operating in large portions close to the shoreline, are prone to criticism for large emission outputs. Cutting emissions can create healthier working platforms and promote fish farming companies and the aquaculture industry as a whole. Finally, cost is a core value factor and the main incentive in most industries. Minimizing costs directly relates to larger profits which ultimately defines the companies' profitability.

As discussed previously, the shipowner must present the best option to the fish farmers to win contracts. This is done by presenting the option that maximizes the stakeholders' overall value. A valuable solution for the described conditions would typically complete all necessary operations with an overall low cost, low emissions and with a high concern for fish welfare.

3.2.1 Fish Welfare

The Norwegian Food Safety Authority states that fish welfare is an important prerequisite for strong fish health, low mortality rates, high product quality, gaining a strong reputation as fish farmers and also for ensuring profitability[41]. Fish welfare is therefore a strong concern for companies managing and operating with live fish[45].

Animal welfare in a broader perspective is often defined by *The Five Freedoms*[15]. They comprise of:

1. Freedom from thirst, hunger and malnutrition
2. Freedom from discomfort
3. Freedom from pain, injury and disease
4. Freedom to express normal behavior
5. Freedom from fear and distress

These freedoms define the basic needs of any living individual, and depriving an individual of one or more of these needs is considered harmful to its life quality.

When it comes to the transport operations of adult salmon, welfare is typically impacted by several operations. In order to get the salmon onboard the vessel, the salmon must first be crowded so that they swim towards and into the pump. Crowding is the act of gradually decreasing the volume of which the salmon can swim, often to the extent of depriving the salmon of their freedom to express normal behavior. This has been proven to increase the salmon's stress levels, depriving the salmon of their freedom from discomfort and from fear and distress[21, 27, 37]. After crowding, pumping is performed, where the salmon is pumped onboard the vessel. Depriving the salmon of the same freedoms as during crowding, pumping has been shown to have the largest effect on welfare during transport operations[27]. It is therefore desired to minimize the number of necessary pumping operations during salmon transport. While onboard a well-boat, the salmon is in a somewhat more familiar environment where the salmon can express normal behavior to some extent. It has been shown that the stress levels can regress close to normal during transport if the transport time is sufficiently long[27, 39].

The increasing of stress levels and muscle activity have been linked directly to low quality of the end product[21, 54]. Especially elevated muscle activity in the hours leading up to slaughter has been proven impactful on the quality. Low quality in this sense means that the salmon fillets are split (gaping) or soft and loose, which are traits that often repel customers.

Mortality rates describe the proportion of salmon that pass away during the production cycle. By the Norwegian regulations on the operation of aquaculture facilities, the mortality rate of each fish farm must be reported to the Directorate of Fisheries for each production cycle[36]. High mortality rates are harmful to the fish farmer's and the industry's reputation, as well as a direct loss of end product and the following income.

Recent focus areas have seen increased interest in fish welfare and animal rights. The aquaculture industry's reputation of disregarding environmental impacts and animal rights, and of over-exploiting natural resources for fish feed, is damaging and affecting customers' willingness to purchase their products[17, 43]. The average customer is demanding higher standards to sustainable production as well as to welfare and environmental regards[43]. It is therefore becoming viable to include fish welfare as a unique performance parameter when making strategic planning decisions. In order to make this feasible, fish welfare must be quantified into a measurable entity.

Fish welfare impacts can, in a general sense, be considered as twofold: physical and psychological[57]. The physical impacts are apparent in the form of damages or death, while the psychological impacts are more hidden. Quantifying the lost value in the loss of a lifeless product for sale is easily done by considering the product's income potential. However, as previously discussed, the death of a farmed salmon has much larger consequences than simply the loss of sale.

Furthermore, welfare impacts like higher stress levels, discomfort and strained behavior that do not result in physical consequences should be addressed to be able to evaluate the complete welfare impact. However, today's technology is not adequate to analyze thoroughly all impacts on welfare due to specific operations[57]. This makes evaluating the psychological impacts challenging. Research has shown that stressful operations cause elevated cortisol, glucose and lactate levels, but to what extent this is harmful to the salmon is yet undefined.

Although the sufficient technology to evaluate non-visual impacts on fish welfare is lacking, it is still fair to imply that depriving the fish of one or more of their core freedoms affects the salmon's life quality. For the fish farmer and for the aquaculture industry, fish welfare brings two main initiatives: not losing valuable product and maintaining a strong reputation. Therefore, the necessary quantification for using welfare as a performance parameter is:

- The direct cost of lost profit from sale due to mortality and damages
- The indirect cost of reputational damage due to low welfare standards

The direct cost of lost profit from a single mortality is assumed equal to the individuals selling price, which is a fair assumption for such a late part of the value chain. The cost of a damaged individual is reflected by the lowered selling price due to visual imperfections. Reputational damage is one of the greatest fears of the aquaculture industry. High quality and a strong reputation is essential when delivering a high-priced product to a competitive market[42]. For the fish farmer, damage to their reputation could affect working relations with other contributors in the value chain, or even impact their ability to acquire new production licenses.

In order to evaluate the actual value of reputational damage, one would likely have to analyze the risk of losing customers and of losing production licenses as well as working partners due to reputational damage. Alternatively, one could question the fish farmers on how much they are willing to pay to reduce the risk of death or damage to their salmon, much like how one statistically values human life in modern risk analyses. This is, however, unexplored in the literature, so a "cost", or cost-equivalent value, of reputational damage will be assumed for practical purposes. This cost-equivalent estimate of the indirect cost of reputational damage is set to be twice as large as the direct cost of a fatality and of a physical damage to the salmon. This is, however, solely an input parameter to the proposed method, meaning that if further analysis is done in this field, the estimates can be updated without affecting the proposed method. Finally the reputational damage of harsh operations leading to psychological impacts on fish welfare must be quantified. These damages aren't apparent to the public to the same degree, meaning that it does not affect the farmers' reputations to the same extent as fatalities and physical damages. Also the extent of value loss in the end product due to higher stress levels is unquantified, so the average combined reputational damage and quality loss to carrying out one "crowding and pumping" operation will be valued at half of the mortality cost.

To summarize, fish welfare is quantified by evaluating direct and indirect costs. If a transport operation by well-boat (with three "crowding and pumping" operations) involves 100 tonnes of salmon, and one assumes a mortality rate of 1‰ and a physical damage rate of 3 ‰ during this operation as well as a selling value of 5 000 USD/tonne and a loss in selling value of 2 000 USD/tonne for damaged salmon, the welfare cost of this transport would be:

$$\text{Direct cost} = 0.001 \cdot 100 \cdot 5\ 000 + 0.003 \cdot 100 \cdot 2\ 000 \ = 1\ 100 \text{ USD}$$

$$\text{Indirect cost} = 0.001 \cdot 100 \cdot 10\ 000 + 0.003 \cdot 100 \cdot 4000 + 3 \cdot \frac{1}{2} \cdot 0.001 \cdot 100 \cdot 5\ 000 = 2\ 950 \text{ USD}$$

$$\text{Total welfare cost} = \text{Direct cost} + \text{Indirect cost} = 1\ 100 + 2\ 950 = 4\ 050 \text{ USD} \tag{3.1}$$

3.2.2 Emissions

According to the most recent IMO Greenhouse Gas Study from 2014, maritime transport has an annual emission of about 940 million tons of CO_2[24]. Global climate change is an increasing issue, but "easy", cost-effective solutions still often prevail over environmentally friendly solutions in most every-day choices both in households and in businesses[35]. However, with the introduction of electric cars and zero-emission vessels, stakeholders are beginning to value the reduction of emissions in transport operations. New regulations and standards are also being introduced at an accelerating rate, and there is reason to believe that stricter regulations on emissions will continuously be introduced to further combat climate change[11, 25].

The calculations of emissions are naturally based on the fuel consumption and the fuel composition. The fuel consumption of an operative vessel is given by the product of the specific fuel consumption and the power output.

$$F \text{ [kg]} = SFC \text{ [kg/kWh]} \cdot P \text{ [kWh]}$$

The power output is dependent on the installed power and the energy consumption rate during sailing and operations. Although emissions of NO_x and SO_x are gaining attention in the maritime industry, the main emission output is CO_2. Therefore, for simplicity, CO_2-emissions will be the focus for this performance parameter, but a more holistic method applying emission weighting models like the Eco-Indicator could be included[30].

The CO_2-emissions can be calculated from the fuel's carbon fraction and by multiplying this with a factor for converting carbon to CO_2[10]. Extensive studies on gram pollutant per gram fuel used for maritime transport were carried out by Lloyd's Register in 1990-1995 and are still widely used for calculations[32]. The equation for the CO_2 output by marine diesel oil (MDO) fuel is given as

$$CO_2 \text{ [kg]} = 3.17 \cdot F \text{ [kg]},$$

where 3.17 is a constant given by the carbon fraction of MDO, 0.864, multiplied with the conversion factor from carbon to CO_2 given as $\frac{44}{12}$ (derived from CO_2 and Carbon's respective molar masses)[32]. From the presented equations, the CO_2-emissions can now be derived from the power output of the vessel. Thus, we can also analyze the relative emissions between different vessel types and vessel sizes by solely considering the power output.

In order to turn fleet emissions into a functional performance parameter, the value of emission reductions must be linked directly to costs, i.e. a cost-equivalent value must be derived for a given reduction in emissions. A study of the cost-emission relation for various fleet compositions with different fuel types operating in the aquaculture industry was carried out by Slette et al. in 2019[59]. This study used simulation as a tool for evaluating the cost of reducing emissions by evaluating how much more a fleet with lower emissions would cost relative to the most cost-effective fleet. This method will be incorporated and run to fit the presented test cases of this thesis in order to quantify the cost of reducing emissions. The actual value of reducing emissions is then decided by the derived cost-emission relation and the stakeholders' weighted interest in reducing emissions from the stakeholder analysis.

3.2.3 Cost

Most industries are driven by the ability to turn a profit on provided services. Profits are made by maintaining high incomes and low costs. Costs are typically divided into two main categories: investment costs and operational costs. The investment costs are costs induced prior to operations and are typically dominated by the cost of buying or building the vessels that make up the fleet. Operational costs consist of all expenditures made during operations. These include, but are not limited to, fuel costs, manning costs, and maintenance costs.

The investment cost, often denoted as CAPEX from capital expenditure, is typically dependent on the vessel type, size and the integrated technology. In this thesis, the investment costs will be derived from a regression analysis of existing vessels in the industry. Due to a tradition of secrecy in the industry when it comes to precise values on investments, only a few good estimates were derived for the regression analysis. Furthermore, the national fleet of well-boats is not very large in Norway, so the sample size is somewhat small. Moreover, the fleet of processing vessels is minuscule. Some processing vessels being introduced today are reconstructed well-boats, which further complicates deriving the investment costs of newbuilds. The presented regression analyses are, however, the best obtainable estimates from the publicly available information. The regression analyses for well-boats and processing vessels are presented in Appendices A.1 and A.2.

The derived relationships between investment cost and cargo capacity for well-boats and processing vessels are presented below.

$$\text{Well-boat CAPEX} = -40x^2 + 97000x - 3000000$$

$$\text{Processing Vessel CAPEX} = -26x^2 + 81000x + 3900000,$$

where the CAPEX is given in USD and x represents the cargo capacity of the newbuild in tonnes. The investment cost can be turned into a Capital Recovery Factor (CRF) which is the annual cost to pay back the investment adjusted for interest. This is useful when considering annual costs or comparing investment costs to other cost factors. The equation for the CRF is

$$\text{CRF} = \text{CAPEX} \cdot \frac{p \cdot (1+p)^n}{(1+p)^n - 1},$$

where p is the market interest adjusted for inflation and n is the expected lifetime of the fleet. An example is that an investment of 10 MUSD with an interest of 7% to be payed back over 25 years would require an annual payment of 0.86 MUSD.

The operational cost consists of an operating cost and a voyage cost[63]. The relative contributions to the overall operational costs vary with transport distance and vessel speed. The operating costs, often denoted as OPEX from operational expenditures, represent the day-to-day expenses of running the fleet, including the cost of the crew (CC), routine repair and maintenance (RM), administration (AD) and insurance (IN). The crew costs typically comprise of roughly half of the annual operating costs, naturally depending on industry and missions specifications[63]. As the crew costs are simple to estimate and the true values of the other cost factors typically are concealed by shipowners, the operating costs will be simplified to the following equation:

$$\text{OPEX [USD/h]} = \text{CC} + \text{RM} + \text{AD} + \text{IN} \approx 2 \cdot \text{CC}$$

Further, the crew cost can be estimated based on the average salary, number of crew members, operating time and overtime costs. The average salary is estimated to 30 USD/h based on the average salary of seamen in Norway[62]. The overtime premium is assumed to be at 100% and is induced if the crew is at sea for more than eight hours per day. Weekend overtime premiums have already been accounted for in the average salary estimate. The manning estimate (ME) depends on the vessel type and size. Based on public information on the present Norwegian fleet of well-boats and processing vessels, the manning estimate is assumed to be 6 persons for vessels with a capacity lower than 400 tonnes of salmon and 10 persons for larger vessels. Now the operating cost can be found through the following relation:

$$\text{OPEX [USD]} = 2 \cdot \text{ME [pers]} \cdot (30 \text{ [USD/h/pers]} \cdot \text{ST[h]} + 60 \text{ [USD/h/pers]} \cdot \text{OT[h]}),$$

where ST denotes the total sailing time per trip up to 8 hours and OT denotes the number of overtime hours.

The voyage costs, often denoted as VOYEX from voyage-related expenditures, represent the variable costs incurred during sailing and operations. For well-boat and processing vessels, these are largely dominated by the fuel cost. The voyage costs will therefore be defined as follows:

$$\text{VOYEX [USD]} \approx \text{Fuel Cost [USD]} = SFC \text{ [kg/kWh]} \cdot F \text{ [USD/kg]} \cdot P \text{ [kWh]},$$

where SFC is the specific fuel consumption, F is the fuel cost and P is the utilized power during voyage. It is assumed that the vessels run on marine diesel oil (MDO). The specific fuel consumption is estimated to 0.18 kg/kWh for MDO[31] and the fuel cost is estimated to 0.8 USD/kg[58]. This results in the following relation for voyage costs:

$$\text{VOYEX [USD]} = 0.144 \text{ [USD/kWh]} \cdot P \text{ [kWh]}$$

Finally, a penalty cost must be included for not carrying out the dedicated missions. This is necessary to award higher performances to fleets carrying out a larger portion of the designated missions. The penalty costs should reflect the financial effect postponed operations have on the fish farmer, either by extra work load, additional feed being used, mortality risks or other extra efforts. In addition, the reputational damage for not carrying out a mission is significant and could affect the shipowner's ability to win contracts in the future. Accurate estimates for these penalty costs are complicated to derive so some simplifications will be done. Since the purpose of the penalty cost is to penalize fleets for not performing their missions, it is naturally necessary for the penalty cost to be larger than the incurred costs during the operation, so that the fleet would rather perform its missions than not. Further, it is convenient for the penalty costs to not be so large that a fleet performing very poorly within all aspects but has 100% mission coverage is given a better overall performance than a fleet performing exceptionally, but has a single postponement during one week of operation. For the sake of the feasibility study, the penalty cost is based on the operating costs and the sizes of the presented cases in Chapter 4. The penalty costs are presented in Table 3.1.

Table 3.1: Induced penalty cost for neglected operation during an operating week.

Operation	**Penalty Cost**	**Unit**
Juvenile transport	5 000	USD/tonne/week
Adult transport	500	USD/tonne/week
Delousing	50 000	USD/operation/week

If a mission is not carried out during the week it was planned, a penalty cost is induced following Table 3.1 and the mission is carried over to the next week.

Now the total annual cost can be found as:

$$\text{Annual Cost} = \text{CRF} + \text{Annual OPEX} + \text{Annual VOYEX} + \text{Annual Penalty Cost}$$

3.2.4 The Impact of Design Decisions on Performance

Following the definitions of the performance parameters, one can now see precisely what design decisions affect the performance of the fleet.

From fish welfare, the vessel type and the following transport method is the decisive design decision. Well-boats have a larger impact on fish welfare due to more harmful operations. When it comes to emissions and the voyage cost, the power output is the decisive variable. Lowering the power output will lower the fuel consumption which is both the main contributor to the voyage costs and directly leads to emissions. The power output is dependent on the installed power and the power consumption during sailing and operations, which again depends on the vessel size and speed. The relationship between the installed power and the cargo capacity is derived by regression analysis of active well-boats and processing vessels in the Norwegian fleet.

The regression plots can be seen in Appendices A.3 and A.4, and the equations are presented for well-boats and processing vessels respectively:

$$\text{Installed Power Well-boat [kW]} = 4.15x + 875$$

$$\text{Installed Power Processing Vessel [kW]} = 2.40x + 950,$$

where x is the cargo capacity in tonnes. These functions yield for the installed speed of a given vessel. Speed increases and reductions are assumed to impact the investment cost and installed power following the relations in Table 3.2:

Table 3.2: Speed alterations and its impact on the installed power and CAPEX

Δ Speed [kn]	**Δ Power [%]**	**Δ CAPEX [%]**
-1	-4	-4
0	0	0
1	6	6
2	14	14

Finally, the operating cost is dependent on the crew size, which again is dependent on the vessel size.

Now that cost estimates have been made and cost-equivalent values of all performance parameters have been derived, it is necessary to understand what performance parameters are considered most important by the stakeholders. This is derived through a stakeholder analysis.

3.3 Stakeholder Analysis

Stakeholder analyses are carried out in order to understand what expectations the different individuals, companies or governing bodies involved in the decision-making have. Understanding what is valuable to all parties involved is key to creating successful co-operations and making sure that all parties are as satisfied with the final solution as possible. Decision-making in naval design processes are typically complex and political, with a high degree of compromises and leveraging. Insight into this process is key to determine what performance parameters create value for the stakeholders. Costs have for a long time been the dominating performance parameter in the industry, but with increased pressure from global sustainability goals (like the UN's Sustainable Development Goals) to include societal and environmental aspects into considerations, an approach for defining success in more ways than simply considering the bottom line is becoming increasingly relevant[7]. The aim of the stakeholder analysis is to understand how highly the stakeholders' evaluate the different performance parameters and derive a weighting of these towards the overall performance.

The stakeholders involved in operations carried out by well-boats and processing vessels typically include:

- The shipowner
- The fish farming companies

- The crew
- The shipyard
- The governing bodies
- The customer
- The salmon

The stakeholders will have different interests in these operations and in order to be able to create value for the stakeholders as a unity, it is necessary to understand how highly each stakeholder values each performance parameter and how influential each stakeholder is with regards to decision-making. The specific interest and influence of each stakeholder may vary from one collaboration to the next. Therefore, one cannot derive weighted expectations that are accurate for all scenarios. Since this is the case, and since the objective of this thesis is to propose a strategic planning method rather than compute highly accurate results for one given case, some assumptions and simplifications will be made in the stakeholder analysis. A core simplifications is that the stakeholders will be regarded as one entity, rather than looking at each stakeholder's individual expectations and then weighting these by the stakeholder's relative influence. This creates the picture that all involved stakeholders have held a meeting prior to decision-making where they have agreed upon their common evaluation of the performance parameters. Weighting averages based on these preferences are now to be derived.

3.3.1 Analytical Hierarchy Process

It is typically difficult to state accurately how highly one evaluates different performance parameters, especially when there are more than two. A strong weighting method for evaluating multiple parameters may therefore be relevant. In this thesis, the Analytical Hierarchy Process, first introduced by Thomas Saaty (1980), will be applied for this purpose[55].

The AHP takes the relative pairwise importance of the parameters and derives a rating based on these. This is especially valuable when one may have conflicting interests, e.g. two stakeholders have opposing opinions, but it is also functional when considering all stakeholders as a united entity. The process also derives a Consistency Ratio (CR) that says something about the validity of the derived weighting averages, e.g. ensures that the stakeholders do not evaluate A over B, B over C, but C over A.

The AHP calculations will now be carried out, and will include the three discussed performance parameters: fish welfare, emissions and costs, and one united group of stakeholders. The relative ratings between the parameters will be based on the Saaty Rating Scale[55]:

Table 3.3: The Saaty Rating Scale utilized in the Analytical Hierarchy Process.

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favor one over the other
5	Much more important	Experience and judgement strongly favor one over the other
7	Very much more important	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

A basic assumption is that if A is absolutely more important than B and is rated at 9, then B must be absolutely less important than A and valued at 1/9. The first step is to derive the pairwise relative importance of the value factors. These are now assumed for the purpose of the feasibility study. By the definitions in Section 3.2, it is assumed that:

- Welfare is much more important than emissions
- Cost is somewhat more important than welfare
- Cost is very much more important than emissions

The matrix of the pairwise importance, often referred to as the Overall Performance Matrix, is presented below.

Table 3.4: The Overall Performance Matrix of the Analytical Hierarchy Process

	Welfare	Emissions	Cost
Welfare	1	5	1/3
Emissions	1/5	1	1/7
Cost	3	7	1

Now the eigenvector, often referred to as the Relative Value Vector, is to be calculated. This can be done in many ways ($Ax = \lambda x$), but a good and fast approximation is found by multiplying together the entries in each row of the matrix and then taking the nth root of the product. This is especially handy when dealing with large matrices. The nth roots are then summed and normalized to create the eigenvector:

Table 3.5: Generating the nth root and the eigenvector for the Analytical Hierarchy Process

	Welfare	Emissions	Cost	Product	nth root	Eigenvector
Welfare	1	5	1/3	5/3	1.186	0.279
Emissions	1/5	1	1/7	1/35	0.306	0.072
Cost	3	7	1	21	2.759	0.649
Sum					4.251	1.000

Since there are three performance parameters, the nth root is here the cubic root. The eigenvector (0.279, 0.072, 0.649) now represents how the stakeholders as a united entity evaluate the performance parameters. Finally, the Consistency Ratio (CR) is desired in order to ensure the validity of the results. Saaty states that a CR close to zero implies that the results are consistent and that a CR above 0.1 indicates that the results are on the verge of consistence[55]. The CR is found by first deriving λ_{max}, which is estimated my multiplying each row in the matrix by the eigenvector and then dividing the result by the row's eigenvector, e.g. the first row gives: $(1 \cdot 0.279 + 5 \cdot 0.072 + \frac{1}{3} \cdot 0.649)/0.279 = 3.065$. The results are shown below:

Table 3.6: Generating λ_{max} estimations for the Analytical Hierachy Process

	Welfare	Emissions	Cost	nth root	Eigenvector	λ_{max}
Welfare	1	5	1/3	1.186	0.279	3.065
Emissions	1/5	1	1/7	0.306	0.072	3.069
Cost	3	7	1	2.759	0.649	3.066
Sum				4.251	1.0000	

Now the best estimate of λ_{max} is the mean of all the estimates found, being 3.067. The Consistency Index is found from the following calculation:

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} = \frac{3.067 - 3}{3 - 1} = 0.034.$$

Finally, the Consistency Ratio is found by dividing the Consistency Index by the corresponding index of consistency for random judgements, which according to Saaty's work, for three performance parameters is equal to 0.58[55], giving:

$$\text{CR} = \frac{\text{CI}}{0.58} = \frac{0.034}{0.58} = 0.059.$$

The derived ratio is well below 0.1, and the results can be concluded as consistent.

3.3.2 The Weighted Values' Significance

Now that the stakeholders' weighted interest has been found for the performance parameters it is relevant to discuss what this means in practice. In Section 3.2, the cost-equivalent value of fish welfare and emissions were discussed. In Subsection 3.2.1, an example was put forth, where the cost-equivalent value of the welfare impacts of a transport operation by well-boat of 100 tonnes of salmon came at 4 050 USD by Equation 3.1. However, it has now been derived that the stakeholders' interests in fish welfare is 0.279 while the interests in cost is 0.649. Therefore, the actual weighted cost-equivalent value of the transport operation is derived as:

$$\text{Weighted Cost-Equivalent Value} = 4\ 050 \cdot \frac{0.279}{0.649} = 1\ 741 \text{ USD}.$$

This depicts the stakeholders' actual evaluation of fish welfare impacts. Likewise, if a vessel operates with 20% lower emissions than the most cost-efficient fleet, and this has been found to have a cost-equivalent value of 1 MUSD, the actual weighted cost-equivalent value of this emission reduction is derived as:

$$\text{Weighted Cost-Equivalent Value} = 1\ 000\ 000 \cdot \frac{0.072}{0.649} = 110\ 940 \text{ USD.}$$

These weighted cost-equivalent values are a way of not just stating what the practical cost of emission reduction measures or of fish welfare improvements are, but of determining what the stakeholders actually are willing to devote to these measures, which creates a much more applicable picture to the fleet size and mix decisions.

3.4 Proposed Method for Solving the Strategic Problem

In this section, a description of the proposed step-wise process for solving the fleet size and mix problem will be given, as well as insights into how the designed models work. A visualization of the step-wise process of the proposed method is presented in Figure 3.1.

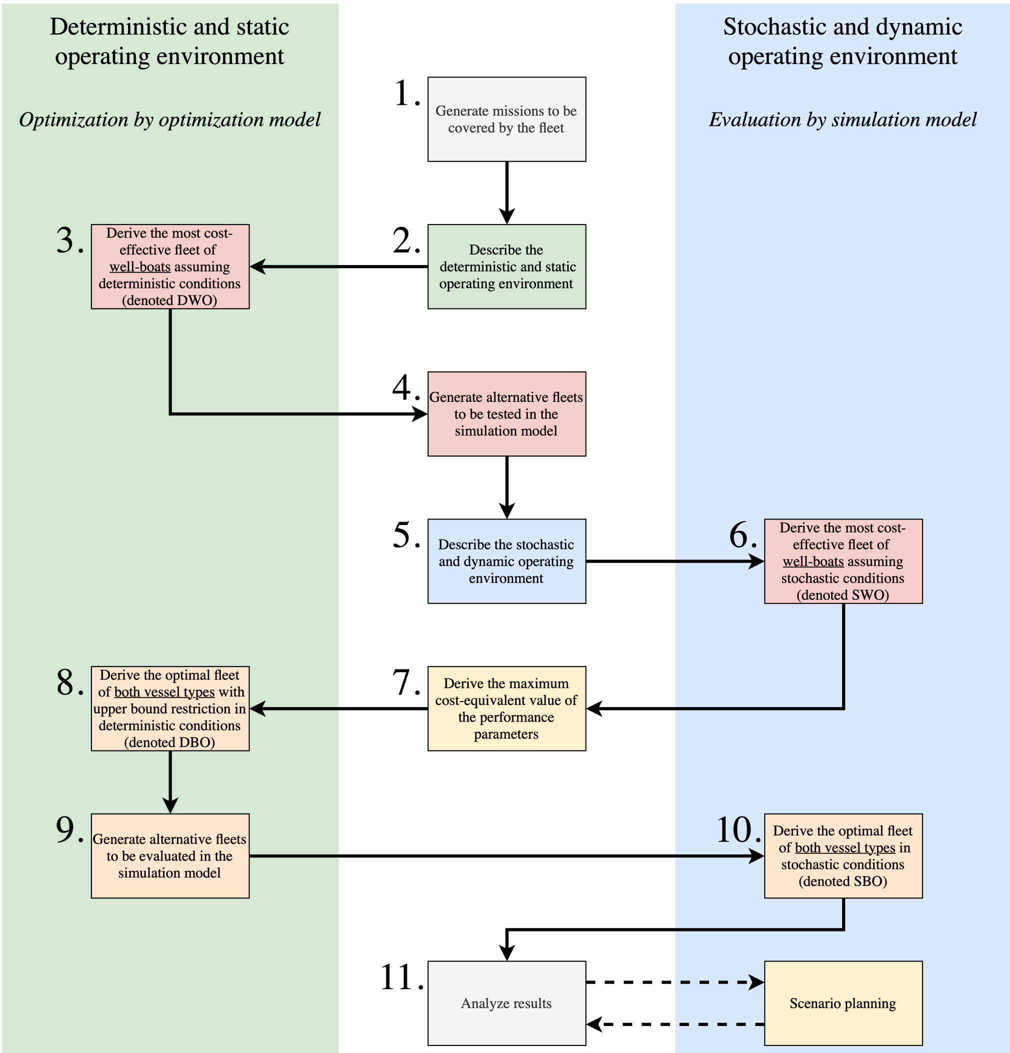

Figure 3.1: The proposed method for solving the fleet size and mix problem

3.4.1 The Process

The overall idea of the proposed method is to use simulation models to capture the stochasticity and dynamics that best reflect the operating conditions for fleets in the aquaculture industry. However, the design space, meaning the number of possible designs for the fleet, is typically massive, considering every combination of vessel characteristics each vessels can have, as well as how many vessels are to be included in the fleet. The introduction of processing vessels makes the design space even larger as it poses the option of a second vessel type. To bode for this, an approach for narrowing down the design space *before* introducing processing vessels is presented. This is done by first deriving the most cost-effective fleet of only well-boats, as seen in steps 3 – 6 in Figure 3.1. Thereafter, realizing that there is a maximum cost-equivalent value that can be generated by the improvement in welfare concerns and emissions posed by processing vessels, an upper bound on costs can be generated for the fleet including processing vessels. This means that a fleet containing processing vessels can never perform better than the cheapest fleet of only well-boats if it is more expensive than the total cost of the well-boat fleet plus the maximum cost-equivalent value that is possible to derive from the other performance parameters. An example is presented in Table 3.7.

Table 3.7: Example of the upper bound on the total cost of the optimal fleet

Parameter	**Value in [USD]**
Total Cost of Well-Boat Fleet	10 000 000
Max Value from Fish Welfare	1 500 000
Max Value from Emissions	500 000
Upper Bound on Costs	**12 000 000**

This approach works especially well because the investment cost of processing vessels generally are larger than for well-boats. If this was not the case, the processing vessels would have a higher performance within all performance parameters, and would consequently always be preferred for salmon transport. Now, however, we have a restricting upper bound on costs for the optimal fleet, meaning that the design space has been narrowed down. Furthermore, since running simulations usually is time-consuming, but necessary to give a more accurate depiction of real events, an approach for narrowing down the design space before initiating the simulations at all is presented. This is done by designing an optimization model that solves the fleet size and mix problem in deterministic conditions. A key assumption is that if this model is designed to represent the average value of all stochastic variables in the simulation model, the optimal solution found from the deterministic conditions is likely to also perform well in stochastic conditions. However, since the impact of the stochastic variables on the fleet performance is yet unclear, the this fleet might not accurately represent a strong solution on its own. Nevertheless, if multiple solutions are derived in the deterministic conditions, e.g. the optimal solution for the analyzed case and some alternative solutions that share some distinct characteristic with this fleet, the derived fleets will represent a range in the design space, which more likely is able to represent a strong solution in the stochastic environment. A visualization of the proposed approach is given in Figure 3.2.

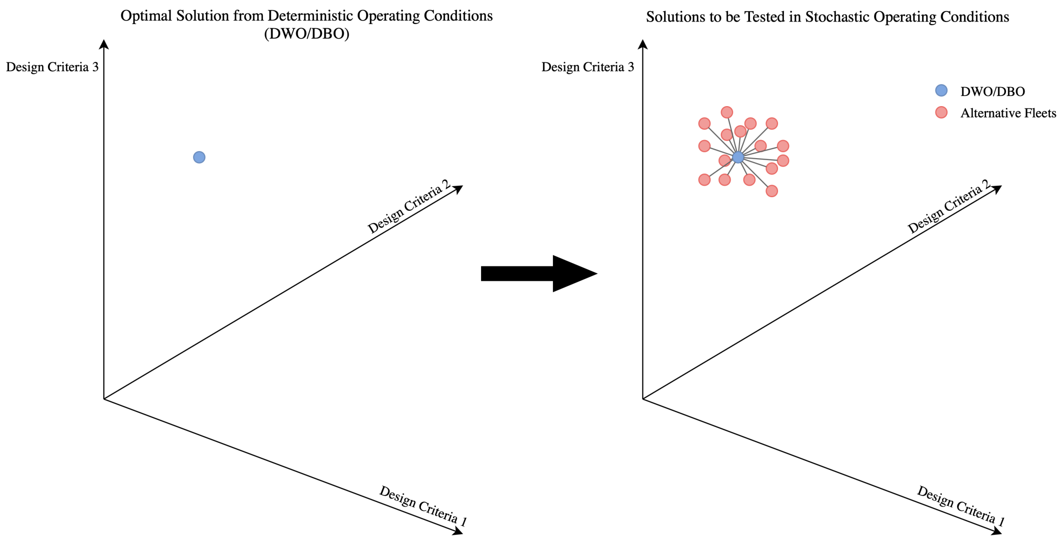

Figure 3.2: Example of pin-pointing in the design space

Using these two approaches to narrowing down the viable design space, we can now follow the steps presented in Figure 3.1 to derive the optimal fleet for the given case considering well-boats and processing vessels. This is done by considering only well-boats before introducing processing vessels and considering a deterministic operating environment before evaluating fleets in the stochastic operating environment. After deriving the mission to be carried out and describing the deterministic operating condition, Step 3 from Figure 3.1 derives the most cost-effective fleet of well-boats in deterministic conditions, denoted the *DWO*. Next, alternative fleets, that are similar but not identical to the DWO, are generated and the stochastic operating environment is described. Then, in Step 6, the most cost-effective fleet of only well-boats is derived from evaluated fleets in the stochastic environment, denoted the *SWO*. As the stochastic operating conditions are more depicting of real events, the SWO represents the fleet of well-boats that performs best in the real world. Step 7 is deriving the maximum value of the performance parameters, as exemplified in Table 3.7. In Step 8 the optimization model is run again for the deterministic conditions, but now including the processing vessels and implementing the upper bound on costs. The optimal solution, now considering fish welfare and emissions as performance parameters in deterministic conditions, is derived and denoted *DBO*. In Step 9, alternative fleets are generated before the fleets are evaluated in the simulation model. Finally, the optimal solution to the fleet size and mix problem from the evaluated fleets is found in Step 10. This is denoted *SBO*.

The steps of this process will now be described in more detail, before the method is applied to three test cases in Chapter 4.

3.4.2 Generating Missions and Operating Environments

Missions are generated on a weekly basis. Each mission is defined by its frequency and the quantity of salmon that is involved in the operation. The frequency of each operation is based on the size of each fish farm and what part of the production cycle the farm is in. The mission frequencies are generated on the basis of information provided by sources from the Norwegian aquaculture industry and are presented and discussed further in Section 4.1.

The operating environments differ in that two main factors of the problem vary in the stochastic environment while they are constant in the deterministic environment. These factors are the sea state and the required missions. In the deterministic environment, the number of operations and the sea states at each fish farm are unchanged and can therefore be completely planned for in the strategic and tactical planning problems. In the stochastic operating conditions the sea state for each fish farm location is drawn from historic data every day using values from the Copernicus database[9]. In addition, there is variance in the required operations, reflecting the fact that this is affected by external factors, including growth rates, maintenance work, disease outbreaks etc. This may cause time delays and accumulate penalty costs.

3.4.3 Deriving the DWO

After generating missions and describing the operating conditions, the next step is to derive the optimal fleet of only well-boats. This is Step 3 in Figure 3.1. First, the DWO is derived by the use of optimization models designed in FICO Xpress. The source code for these models are included as an attachments to this report. The optimization model solves the fleet size and mix problem as an integer problem where the model reads a text file of 200 different well-boats to choose from. The applicable well-boats have capacities ranging from 100 to 600 tonnes with an interval of 10, and each capacity has four different options for service speed. The text file also supplies all relevant info on the fish farms, including its locations, necessary missions, and sea states.

The restrictions applied to the optimization model is given below:

- Only six missions are to be assigned each vessel per week
- All missions are performed
- Only vessels with the required operational limit can operate at a given sea state

The operational limit of a vessel defines what sea states the vessel is able to operate at. The sea states are derived from scaling the significant wave heights at the locations to sea states ranging from 1 to 5. The vessel's operational limit is based on the vessel size and ranges from 2 to 4. Thus, a vessel with the operational limit of 3 would be able to operate at sea states 1, 2, and 3, but not at 4 and 5

Since the derived fleets from the optimization models are to be deployed in a stochastic environment, it is assumed that the vessels initially acquire a maximum of six missions per week with one day to spare for carrying out operations postponed by harsh weather. This was found optimal during test runs of the model as acquiring seven missions a week too often resulted in accumulated penalty costs and five missions per week often resulted in vessels spending time in port without missions. It is further assumed that a vessel only has time to carry out one operation per day. This assumption is typically strong, as the sailing and operations collectively deem time-consuming, and with biological safety being an increasing concern, it is usually rare that a vessel operates at several farms at the same day.

The optimization model now derives the most cost-effective fleet (DWO) and the routing of these vessels by using the Branch & Bound method. Since only well-boats are considered here, the cost-equivalent values of emissions and fish welfare are not yet considered. Instead of creating a mixed integer problem where the vessel characteristics pose as decision variables, it was found effective with regards to computational time to rather model an integer problem with the possible vessels already given. As optimization is only done in deterministic conditions, and the actual optimal solution is found from the stochastic operating environment, the choice of pre-defining applicable vessels is seen as a functional simplification.

Routing is solved by generating one route per operation per fish farm, e.g route 1 being a delousing operations at fish farm 1 and route 2 being salmon transport, and then making sure that all routes are covered enough times to reflect all missions being carried out. From the source code, it can be noted that the optimization model considers a three week period, i.e. the generated missions are the missions required for three weeks of operation. This was done to better reflect that the number of required operations change according to how far along in the production cycle each farm is, i.e. if a farm requires three delousing operations per week for the first 2/3 of the production cycle and two operations for the final third, then the farm requires on average eight operations over a random three week period.

3.4.4 Designing Alternative Fleets

Now that the DWO has been derived, alternative fleets will be computed as discussed in Subsection 3.4.1 and visualized in Figure 3.2. The DWO is the most cost-effective solution in the deterministic environment, i.e. the fleet with the smallest leeway. Since accumulating penalty costs is more severe than having an extra day in port without missions, it is fair to assume that fleets that are smaller in size than the DWO will struggle to compete in the stochastic environment. Therefore, the generated alternative fleets are designed to be larger in size and/or have a larger cruising speed to possibly counteract weather delays or extra missions. This induces larger costs and emissions, but may limit the incurred penalty costs.

The method for deriving alternative fleets that are similar to the DWO is somwehat simplistic in this thesis. As the overall objective is to propose a functional method for solving fleet size and mix problems rather than to derive precise results for a specific case, the simplified approach is seen as functional with regards to the feasibility study. The applied approach for deriving alternative fleets of well-boats is described in Table 3.8.

Table 3.8: The first 13 fleets generated for simulations: the DWO and 12 alternatives.

Fleet	**Adjustment made to the fleet**	**Example of vessels in the fleet**
1	This is the DWO	1, 3, 60, 129
2	Increase all vessels in size or speed by using the second next vessel number from the optimal solution	3, 5, 62, 131
3	Add one extra vessel of capacity 100 tonnes to the optimal fleet (#1)	1, 1, 3, 60, 120 9
4	Add one extra vessel of capacity 320 tonnes to the optimal fleet (#89)	1, 3, 60, 89, 129
5	Add one extra vessel of capacity 480 tonnes to the optimal fleet (#153)	1, 3, 60, 129, 153
6	Increase all vessels of Fleet 2 in size or speed	5, 7, 64, 133
7	Add one extra vessel of capacity 100 tonnes to Fleet 2 (#1)	1, 3, 5, 62, 131
8	Add one extra vessel of capacity 320 tonnes to Fleet 2 (#89)	3, 5, 62, 89, 131
9	Add one extra vessel of capacity 480 tonnes to Fleet 2 (#153)	3, 5, 62, 131, 153
10	Increase all vessels of Fleet 6 in size or speed	7, 9, 66, 135
11	Add one extra vessel of capacity 100 tonnes to Fleet 6 (#1)	1, 5, 7, 64, 133
12	Add one extra vessel of capacity 320 tonnes to Fleet 6 (#89)	5, 7, 64, 89, 133
13	Add one extra vessel of capacity 480 tonnes to Fleet 6 (#153)	5, 7, 64, 133, 153

Table 3.8 shows how fleet 1–13 are generated. To create more alternative fleets, the optimization model is run while increasing the constant sea state at some of the largest fish farms. This creates a new DWO, designed for somewhat rougher operating conditions. Now the same procedure is done as described in Table 3.8 to generate 12 alternatives to this fleet, i.e. fleets 15–26. The same procedure is repeated once more while increasing the sea state at some of the other fish farms to create fleet 27–39. This gives 39 fleets to be evaluated in the stochastic operating environment, which represents a significant part of the design space while limiting the computational time.

3.4.5 Deriving the SWO

The initialization of the simulation process is done by a MATLAB-script, which can be found as an attachments to this report. The MATLAB-script reads the results derived from the optimization model through Excel-files, including both what vessels each fleet consists of, and the routing of these vessels. The generated alternative fleets are given the same vessel routing as the optimal fleet, i.e. Fleets 2–13 have the same routing as Fleet 1 (the DWO), Fleets 15–26 has the same routing as Fleet 14, as this was the optimal fleet with larger sea states, and Fleets 28–39 have the same routing as Fleet 27. For the alternative fleets where vessels have been added to the fleet (see Table 3.8), this vessel is given six operations on a single route. This is taken care of in the simulation model, as if there are no more operations to be carried out on a route, the vessel will look for other available missions. This is an imperfect way of handling the routing problem, and is only used as a simplification for the fleet of well-boats. The routing approach is improved when introducing processing vessels. The MATLAB-script also reads the information on the size and position of each fish farm for the relevant case, before it initiates the simulation model. A preview of the simulation model for the smallest test case, later presented in Chapter 4, is given in Figure 3.3. In this case, there are 10 fish farms as seen in pink to the right of the model.

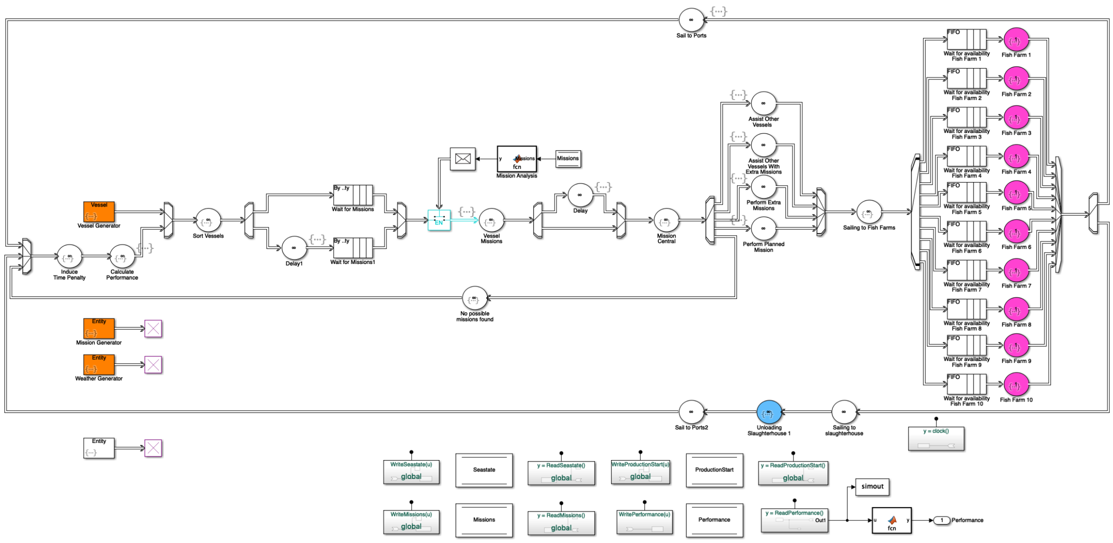

Figure 3.3: The simulation model for Case 1 designed in MATLAB SimEvents

As the simulation model is initialized, the vessels of the simulated fleet are generated as entities to run through the model. The missions are generated at the start of each week from the *Mission Generator* and sea states are generated at the start of each day from *Weather Generator* seen in orange at the bottom left in Figure 3.3. In addition, during initialization, a random week of production start is derived for each fish farm, ranging from week -77 to week 0. This is done to best represent the real life scenarios, where production cycles of different farms rarely are aligned.

As the simulation starts, the vessels are sent through the round-trip model as seen in Figure 3.3. The vessels arrive at the *Vessel Missions*-port where they are given their weekly mission lists. Further, the vessels arrive at the *Mission Central*-port where the vessels check if they are able to perform one of their designated missions on the current day, based on the weather conditions and whether or not there are missions left. As one can see in Figure 3.3, leaving the *Mission Central* can result in four different alternatives. The vessel will always carry out a "planned mission" if this is possible. If this is not possible, the vessel will attempt to carry out an "extra mission", which is a mission at a farm that the vessel already visits that has been induced by the variance in missions. If this is not possible either, the vessel seeks to assist other vessels in performing their extra missions. Finally, if all other options are not applicable, the vessel can seek to assist other vessels in carrying out their planned missions. The last two options are both especially useful if a large vessel has no more missions to perform and can help a smaller vessel with a lower operational limit to carry out missions during periods of rougher sea states, e.g.

during winter. The ports denoting what kind of mission the vessel is to carry out is only for visual purposes, and no calculations are done before the vessels arrive at the fish farm.

After deciding on its mission, the vessel sails to the relevant fish farm, performs its mission, and sails back to port, directly or via the slaughterhouse depending on what mission the vessel is performing. Vessels carrying out juvenile transport would in practice have to go via the hatchery, which is not included as a separate port in the model. No calculations would be done at the hatchery, so this is simply induced as extra sailing distance and induced unloading time at the fish farms. When arriving back to port after finishing its operation, each vessel's performance is analyzed and logged. First, overtime costs are induced if relevant, before the operating costs, emissions and fish welfare impacts are calculated and logged in the final port named "Calculate Performance". At the end of each week, if there are still unfinished missions left, a penalty cost is induced and the unfinished missions are carried over to the next week.

The simulation is run for an operating period of 78 weeks, representing a full sea-based production cycle for the fish farms. When the simulation is finished, the fleet's total performance is sent back to the MATLAB-script that first initiated the simulation. The MATLAB-script logs the performance of the fleets and presents the SWO after all fleets have been simulated.

3.4.6 Deriving the Maximum Cost-Equivalent Value from the Performance Parameters

Now that the SWO has been derived, the next step of the process is to derive the maximum cost-equivalent value from the performance parameters. This is described as Step 7 in Figure 3.1. As indicated in Subsection 3.4.1, this value is derived by comparing the SWO to the performance of a fleet of only processing vessels.

The total CO_2-emissions and the cost-equivalent value of the welfare impacts of the SWO are available from the calculated performance in the simulation model. In order to be able to find the relative cost-equivalent values, the emissions and welfare impacts of a fleet of only processing vessels with the corresponding size must be derived. This fleet would be able to carry out all transport missions, being the same size as the SWO, but would in practice be unable to carry out the other operations. Therefore, this approximation is an overestimate on the actual maximum value of the performance parameters, meaning that less of the design space is removed by the derived upper bound.

The most accurate way of deriving the emission output of a fleet of only processing vessels would be to run a simulation for the SWO, only altering the vessels as to having lower power output to represent processing vessels. However, as these results are only used as a tool to reduce the design space, we do not require accurate results. Therefore, the average installed power of the vessels in the SWO will be compared to the average installed power of processing vessels with the same speeds and capacities. This assumes that the vessels in the fleet spend close to the same amount of time on operations and sailing during the simulated period. Since the CO_2-emission is a function of only the power output, the relative power output also reflects the relative CO_2-emissions.

The next objective is to calculate how much the reduction in emissions is worth. This will be done by running simulations of the 39 well-boat fleets with different combinations of fuel types for each vessel. Fuel types with lower CO_2-emissions than MDO, like LPG or hydrogen, typically induce larger voyage and investment costs. By running simulations with different combinations of fuel types, a good estimate of the cost of emission reductions can be found. This reflects the cost-equivalent value of emission reductions, which must then be weighted by the stakeholders' interest in investing in such measures, as discussed and exemplified in Section 3.3.

It is somewhat simpler to derive the cost-equivalent welfare value for the fleet of processing vessels, as the processing vessels will transport the same quantity of salmon as the SWO. By assuming the mortality and damage rates for transport by processing vessels, the cost-equivalent welfare value of the transported quantity can be derived be the equation in Equation 3.1. The relative cost-equivalent value earned by transporting the quantity by processing vessels must now be weighted by the stakeholder's interests to derive the maximum cost-equivalent value from fish welfare.

By summing the derived cost-equivalent values of emissions and fish welfare, the maximum cost-equivalent value of the performance parameters has been derived, as exemplified in Table 3.7. Now the new upper bound on the maximum cost of a fleet can be implemented into the optimization model when introducing processing vessels.

3.4.7 Deriving the Optimal Fleet (DBO and SBO)

With the new restriction on the fleet cost, the design space has been narrowed. Now, in Step 8 in Figure 3.1, the optimization model is run with the upper bound restriction on costs while including both vessel types. In addition, some changes have to be implemented as processing vessels now are considered. The added restrictions are presented below.

- Only well-boats can carry out delousing operations
- Only well-boats can carry out juvenile transport
- Only processing vessels can carry out fish saving operations

The new "fish saving"-operation, introduced in Subsection 2.2.2, is implemented as a mission that one is not contracted to carry out, but one can perform them if there is time to create more value, representing a spot market. Furthermore, the vessel-specific calculations of the performance parameters are implemented, e.g. lower mortality and damages to salmon during transport by processing vessels.

After deriving the DBO, alternative fleets must be generated for evaluation in the simulation model (Step 9). However, the alternative fleets cannot be generated by the same approach as for the fleet of well-boats, as including an extra vessel of any kind may violate the upper bound restriction on costs, which means generating a fleet that cannot be optimal. Therefore, the approach for generating the alternative fleets is altered to gradually cutting out small parts of the design space. To exemplify, if the DBO has vessels #3, 21 and 57, then the first alternative fleet would have a restriction on not being allowed to include vessel #3 from the list of vessels. This would force the optimization model to find an alternate solution, e.g. including vessel #2, 21 and 63. Different parts of the design space are cut off while ensuring that no identical fleets are generated. Also here, 39 fleets are generated in total, with the last 26 being subject to larger sea states, following the same approach as described in Subsection 3.4.4.

After generating the fleets to be evaluated in the simulation model, the simulations are run. We are now at Step 10 from the flow chart in Figure 3.1. The layout of the MATLAB-script and the simulation model is more or less identical to the ones used for finding the SWO, and can be seen as attachments to this report. By the same process as for deriving the SWO, the simulation model derives the optimal fleet (SBO) for the given case by evaluating the 39 fleets.

3.5 Scenario Planning

The SBO describes the fleet with the highest performance in the given conditions. However, the aquaculture industry, like most industries, is dynamic and prone to changes. These changes may be a consequence of many factors, including the market situation, regulatory conditions, technology advancements and environmental aspects. The fact is that one cannot with certainty say what exact operating conditions the fleet will be operating in 5, 10 or 20 years from now.

Understanding uncertainty and its impact on fleet performance during its lifetime is vital to create robust, successful designs. Robust design is designing to make the final product consistent when the process is subject to a variety of noise[34]. In practice, for fleet design this means that a fleet also performs well in possible future scenarios where changes affect the operating conditions. For strategic planning decisions it is often valuable to perform some form of scenario planning. If the derived optimal fleet for the current conditions performs poorly in general for the most likely future scenarios, it may be advantageous to rather choose a sub-optimal solution for the current conditions that performs better in future scenarios.

The Epoch-Era Analysis is a much discussed approach to handling future uncertainty. It is designed to clarify the effects of changing contexts over time on the perceived value of a system in a structured way[51, 53]. The fundamental building blocks of the Epoch-Era Analysis is the *epoch*. An epoch is a static period in which the system operates, and is defined by *epoch variables*. Epoch variables are described as any change that has an effect on the systems perceived value.

Assembling a sequence of multiple epochs presents an *era*. The era poses as a possible progression of contexts over time, representing a long-term set of multiple short-term changes. Evaluating fleet performance across several eras will give an indication of what fleet designs that are likely to perform consistently over several possible future scenarios.

3.5.1 Epoch Construction

The number of possible epochs (unfolding the so-called epoch space) is defined by the epoch variable and its range. An example is to consider two epoch variables: Change in demand, and change in sailing distance, and the variables each are defined by a range of three possible quantities, e.g. 20% increase, 20% decrease and no change. The number of epochs would be three squared, i.e. nine. A visualization is given in Figure 3.4.

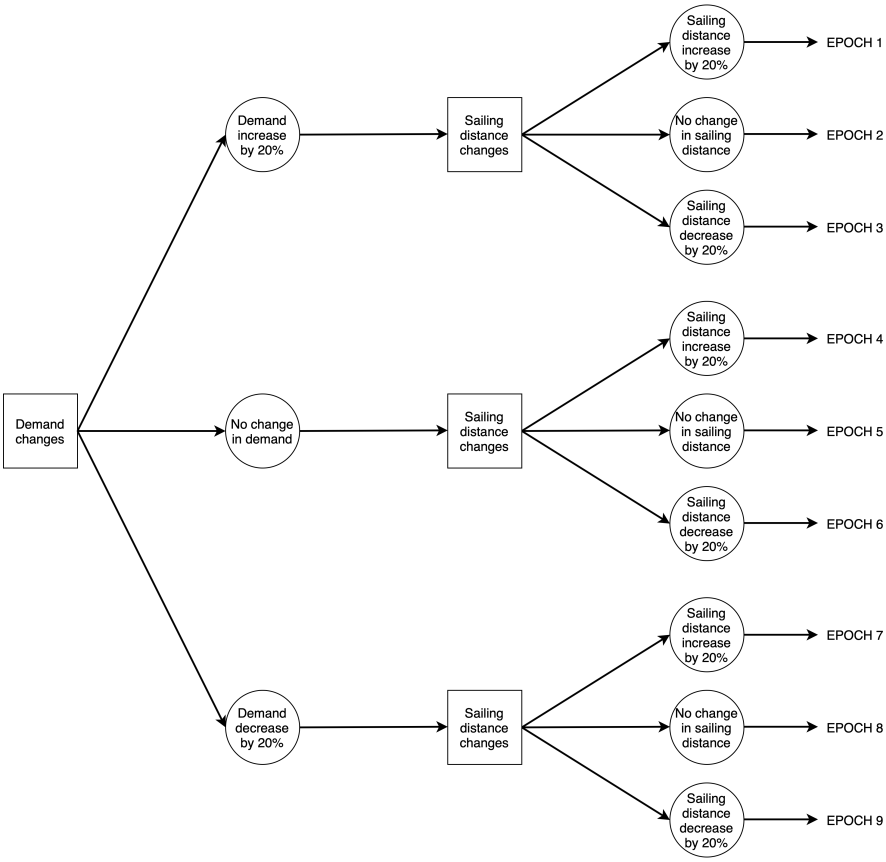

Figure 3.4: Illustration of the exemplified epoch space

Now, if the range consisted of ten possible values for each epoch variable, the epoch space would include 100 epochs. This would naturally give a more holistic analysis, but then including all epochs into eras and analyzing these would be intensely time-consuming. For the feasibility study, the number of epoch variables for each possible change will be limited to three, and only a few eras will be analyzed, as the aim is to prove the value of scenario planning rather than derive profoundly sound results.

To carry out an Epoch-Era Analysis, the epoch variables must be defined, as well as their ranges. There is a large variety of epoch variables that could be relevant in the aquaculture industry, but the ones described in Table 3.9 are assumed to be most relevant:

Table 3.9: Defined epoch variables

Epoch Variable	Source of Uncertainty	Change	Description	Impacts on Operation
Movement to offshore locations	Legislative, environmental and/or market	+ 50%	50% of fish farms move offshore	Increase in sailing distance, farm size and sea state
		+ 20%	20% of fish farms move offshore	Increase in sailing distance, farm size and sea state
		0	No change	
Stakeholder evaluation of fish welfare	Legislative, environmental and/or market	+ 100%	Double importance	More important to minimize impacts on fish welfare
		- 50%	Half importance	Less important to minimize impacts on fish welfare
		0	No change	
Stakeholder evaluation of emissions	Legislative, environmental and/or market	+ 100%	Double importance	More important to minimize emissions
		- 50%	Half importance	Less important to minimize emissions
		0	No change	
Enhanced well-boat technology lowering impact on fish welfare	Technology	- 50%	50% mortality and damage decrease	Well-boats perform better within fish welfare aspects
		- 20%	20% mortality and damage decrease	Well-boats perform better within fish welfare aspects
		0	No change	
Sea-lice problem affects demand	Market and/or technology	+ 20%	Demand increase of 20%	Larger amount of required operations
		- 20 %	Demand decrease of 20%	Smaller amount of required operations
		0	No change	

This defines an epoch space consisting of 243 (3^5) epochs. It is reasonable to define only a few epochs as relevant for further analysis to limit computational time. These epochs are presented below.

Table 3.10: Relevant epochs for further analysis

	Epoch Variables					
Epoch	**1**	**2**	**3**	**4**	**5**	**Description of Impact**
0	0	0	0	0	0	No changes happen
1	+20%	0	0	0	0	20% of the fish farms move offshore
2	0	+100%	0	0	0	Double interest in fish welfare
3	+20%	0	+100%	0	0	Moving offshore, emissions more important
4	0	0	0	-50%	0	50% mortality and damages decrease
5	0	0	0	0	+20%	20% increase in demand
6	0	0	0	0	-20%	20% decrease in demand
7	0	+100%	0	0	+20%	Demand and fish welfare interest increase
8	0	+100%	0	-50%	+20%	Demand, welfare interest, mortality affected

3.5.2 Era Construction

As already stated, the eras consist of a sequence of epochs. There are several ways of constructing eras, typically divided into computational and non-computational methods as well as probabilistic and non-probabilistic methods. For this thesis, a non-computational method often referred to as the narrative approach will be used. This is a subjective way of constructing eras based on what the designer, stakeholders or other people involved believes to be realistic future contexts. This is a simpler approach than many of the computational methods, and while being time-saving, it is also often just as functional as computational methods when the derived results already are based on several assumptions and simplifications. The defined eras are presented in Table 3.11.

Table 3.11: Defined eras for further analysis

	Expectations	**Epoch**	**Start**	**End**
Era 1	No change for the first three years	0	2020	2023
	Increased interest in fish welfare	2	2023	2032
	Well-boat technology enhanced	4	2032	2045
Era 2	Sea-lice problem increases	6	2020	2023
	Movement to offshore locations	1	2023	2030
	Increased interest in emissions	3	2030	2045
Era 3	Sea-lice problem decreases	5	2020	2030
	Increased interest in fish welfare	7	2030	3035
	Well-boat technology enhanced	8	2035	2045

The epoch number given in Table 3.11 relates to the epoch definitions presented in Table 3.10. One can see from Table 3.11 that the eras are defined by narratives based on a logical string of events. E.g. in the first era, the increased interest in fish welfare drives technology advancement, resulting in enhanced well-boat technology, lowering the mortality and damage rates for the transport operations. In the second era, the sea-lice problem drives the industry to moving parts offshore, which further drives an increased interest in emissions due to the increased sailing distances. These eras all describe different sequences of concrete changes that affect the performance of the fleets and will be used for evaluating the fleets robustness.

3.5.3 Metric for Value Robustness

In order to evaluate the performance of the fleets in the constructed eras and its importance relative to their performance in today's conditions, a suitable metric is necessary. In Epoch-Era analyses it is common to construct Pareto fronts, where the system performance is given as a function of the cost. The Pareto front then describes the best solution for each cost value. This way the robustness metric is derived by considering the number of times each fleet appears on the Pareto front, i.e. is "Pareto optimal" for the considered eras. This metric is usually referred to as the Normalized Pareto Trace[18]. Pareto fronts are useful when the stakeholders' incentive to invest is not yet determined, because the method presents the optimal fleet for all given costs. However, for the method described in this thesis, the stakeholders' incentive to invest is already determined through the stakeholder analysis and the definitions of the performance parameters. Therefore, presenting the fleets in a performance-by-cost plot is not as functional. The principle of the Normalized Pareto Trace could be implemented by evaluating how often the fleet is optimal through the different eras. However, when only evaluating three eras, this may lead to multiple fleets being optimal only once. Further, it does not give any information on how poorly the fleet performs when it is not Pareto optimal. Therefore, a different metric for value robustness is desired. For the sake of the feasibility study, the eras will simply be weighted by their presumed relevance. This is a subjective way of evaluating robustness that is based on the stakeholders' anticipation of future scenarios, but as a narrative approach is used for era construction, this evaluation will be prone to subjectivity none the less.

Chapter 4

Feasibility Study

The feasibility study is carried out to test the proposed method in realistic operating conditions and to verify its purpose. The study covers relevant operations for three different cases of different sizes.

4.1 Setup and Assumptions

Within a given operational area, fish farms, hatcheries, slaughterhouses and ports are located. The setup of the different test cases are given by Table 4.1.

Table 4.1: The size of the cases used to test the proposed method

Case	Fish farms	Hatcheries	Slaughterhouses	Ports	Operating Area
1	10	1	1	2	25nm x 50nm
2	20	1	2	4	50nm x 50nm
3	40	2	3	8	50nm x 100nm

The ports function as the starting and ending position of each day for the vessels. The hatcheries provide the juveniles and the slaughterhouses receive the adult salmon. The ports, hatcheries and slaughterhouses are assumed to have no capacity limits, meaning that the ports can receive all vessels in the fleet, the hatcheries can provide the demand of juveniles and the slaughterhouses can receive all the delivered salmon. The frequency of each mission depends on the fish farm size and how far along in the production cycle the farm is. The farm size is defined by its number of fish cages. This number is drawn randomly ranging from 4 and 12 for each farm, with the number of cages always being even as this is common in the industry. The characteristic of each fish farm, i.e. the size and locations, can be seen in Appendix B. All cages are assumed to be identical, with a biomass capacity of 200 000 fish. Juveniles are assumed to be delivered at 100 g, although fish farmers typically vary the juvenile size depending on site exposure and feeding strategy. It is also assumed that all juvenile transport is done during the first week of production although some farmers spread the juvenile transport over several weeks to diversify the salmon size and limit the risk of spreading diseases or having accidents. The adult salmon delivered to the slaughterhouses is set to be 5 kg which is close to the national average[66]. For simplicity, the mortality rate during the sea-based production cycle is set to 0 %, meaning that all 200 000 juveniles in each cage is delivered for slaughter at 5 kg. The mortality during transport operations (including crowding and pumping) is set to 1 ‰ for well-boats and 0.5 ‰ for processing vessels, and the proportion of damaged salmon during transport is set to 3 ‰ for well-boats and 1.5 ‰ for processing vessels. These estimates are rough, as the literature on mortality and physical damage during precise operations is scarce. It is assumed that mortality leads to the complete loss of product, costing the entire sum of sale at 5 000 USD/tonne and that physical damages to the product leads to a loss of 2 000 USD/tonne.

For each farm, the starting time of the first production cycle is drawn at random. After the production cycle of 1.5 years (roughly 78 weeks), there is a quarantine period of four weeks in order to ensure that no diseases are carried to the next generation of salmon and to limit the benthic impact at the location [40].

For simplicity, it is assumed that all vessels in the fleet can operate on all days. This is not the case in practice as all vessels have to expect some days off due to maintenance. It is assumed that the vessels have an energy consumption rate of 75% of the installed power during sailing and 20% during operations. The different missions are defined by their starting and ending time in the production cycle as well as the frequency of which the missions need to be carried out. For example, delousing operations may be carried out from the first few weeks after juvenile deployment until the very last week of production while the first adult transport may happen after about a year of growth.

The functions used for generating missions are based on information on routines and common practice provided by sources in the Norwegian aquaculture industry.

Juvenile Transport

The extent of juvenile salmon transport operations are dependent on the size of the fish farm, i.e. how many cages are at the farm. Since it has been assumed that juveniles are transported at 100g and that there are 200 000 individuals per cage, the simple equation of the single required juvenile transport is given as

$$\text{Juvenile Transport [tonnes]} = 200\ 000 \cdot 10^{-4} \cdot \text{Cages} = 20 \cdot \text{Cages},$$

e.g. a fish farm consisting of 10 cages would require a juvenile transport of 200 tonnes. It has here been assumed that the juvenile transport happens as one single operation.

Delousing

Delousing operations typically depend on how far along in the production cycle the fish farm is, i.e. how large the salmon is. Therefore, one equation is presented for the first 2/3 of the production cycle and another for the final third. The number of operations for the first 2/3 of the production cycle is given by:

$$\text{Delousing operations per week} = \frac{\text{Cages}}{10},$$

and for the final third:

$$\text{Delousing operations per week} = \frac{\text{Cages}}{4}$$

Since the number of missions should be an integer, the number of operations is rounded up, meaning that a farm with ten cages would require one weekly delousing operation in the first part and three operations in the final part of the production cycle.

Delousing strategies typically depend on the fish farm's locations, not just how far it is from shore, but also at what latitude it is located. The need for delousing operations typically vary a lot along the Norwegian coastline. Therefore, these frequencies are only relevant to some situations and should be altered to fit the relevant case.

Fish Saving

The fish saving operation is only relevant when fish must be saved from strong external pressure. This would most often be from the outbreak of diseases, but could also be from other factors like the recent massive algal blossom in Northern Norway that killed almost 8 million salmon[28]. The fish saving operation is somewhat rare and has been accounted for in the simulation model as follows:

- A random number from 1 to 100 is drawn
- If the farm size, i.e. the number of cages at the farm is larger than the drawn number, one fish saving operation is generated.

For a fish farm of ten cages this would induce a fish saving operation about every ten weeks. By drawing a random number from 1 to 100, the number of fish saving operations at each farm is not unique to that farm, e.g. if the drawn number is 5, there will be a fish saving operation at all farms of six or more cages. This is seen as a functional representation of the real events, as disease outbreak or other external events rarely affect only one fish farm. It is assumed that the quantity of salmon to be "saved" always comes at 10 tonnes, and that the saved value of the product is 2 000 USD/tonnes.

Adult Salmon Transport

As there are in total 200 000 salmon in each cage, this becomes 1 000 000 kg or 1 000 tonnes of adult salmon to be transported per production cycle. However, as the transport operations typically are performed for about 25 weeks, this becomes about 40 tonnes per week per cage for 25 weeks.

$$\text{Salmon transport [tonnes/week]} = 40 \cdot \text{Cages}, \tag{4.1}$$

e.g. if there are ten cages at a fish farm, it requires a transport of 400 tonnes per week for the final 25 weeks of production. For the first 53 weeks, no adult salmon transport operations are required.

An example of the frequencies and sizes of different operations for the fish farm with ten cages is summed up in Table 4.2.

Table 4.2: Example of frequency and size of operations for a fish farm with ten cages.

Operation	Starting Time	Ending Time	Frequency	Biomass
Juvenile transport	Week 1	Week 1	1 op/week	200 tonnes
Early stage delousing	Week 1	Week 52	1 op/week	<100 tonnes
Late stage delousing	Week 53	Week 78	3 ops/week	<100 tonnes
Fish "saving"	Week 1	Week 78	1 op/week	10 tonnes
Adult transport	Week 53	Week 78	TBD	400 tonnes

Note that the frequency of adult transport is dependent on the vessel(s) carrying out the operations, e.g. one vessel with a cargo capacity of 400 tonnes would be able to perform the mission with only one visit, while smaller vessels would require multiple trips. It has been assumed that delousing operations never involve more than 100 tonnes of salmon, meaning that if 200 tonnes of salmon needs delousing, this is represented by two delousing operations. The viability of this assumption is discussed in Section 5.2

As discussed in Subsection 3.5.3, eras defined for the Epoch-Era Analysis will be weighted by their presumed relevance. For the feasibility study, the weighting averages are given by Table 4.3.

Table 4.3: The weighting of the different eras.

Era	Weight
0	1
1	0.3
2	0.2
3	0.2

Where Era 0 denotes the "current" operating conditions simulated for when deriving the optimal fleet. It is reasonable to weigh the current conditions heavily, as these conditions are certain. It is, of course, impossible to predict for how long these conditions are unchanged, but all other eras are purely sequences of possible changes, so there is a larger uncertainty connected to these eras. The overall performance of the fleets considering value robustness is thus given by

$$\text{Overall Performance} = P_0 + 0.3 \cdot P_1 + 0.2 \cdot P_2 + 0.2 \cdot P_3,$$

where P_0 is the fleet's performance in Era 0, P_1 is the fleet's performance in Era 1, and so on.

4.2 Results

Each test case is now run with the described setup and assumptions defined in Section 4.1. The results are presented for each step of the method described in Figure 3.1.

4.2.1 Deriving The Optimal Fleet of Well-Boats (DWO and SWO)

The first steps include deriving the DWO and SWO. This is done by first considering a deterministic operating environment using an optimization model. The optimal fleets for each case can be seen in Table 4.4.

Table 4.4: The DWO for the presented cases, where Cap denotes vessel cargo capacity and OL denotes the operational limit of the vessel.

Case 1				**Case 2**				**Case 3**			
Cap [tonnes]	Speed [kn]	OL [-]	Power [kW]	Cap [tonnes]	Speed [kn]	OL [-]	Power [kW]	Cap [tonnes]	Speed [kn]	OL [-]	Power [kW]
320	10	3	2115	400	11	4	2434	480	11	4	2752
300	10	3	2035	300	10	3	2035	320	10	3	2115
100	10	2	1367	300	10	3	2035	300	11	3	2120
100	8	2	1238	100	10	2	1367	300	10	3	2035
				100	9	2	1290	300	10	3	2035
				100	8	2	1238	300	10	3	2035
				100	8	2	1238	100	11	2	1471
				100	8	2	1238	100	11	2	1471
								100	10	2	1367
								100	10	2	1367
								100	10	2	1367
								100	10	2	1367
								100	9	2	1290
								100	8	2	1238
								100	8	2	1238
								100	8	2	1238
								100	8	2	1238
Total Cost [MUSD]			**11.92**				**21.61**				**47.42**

Next, the fleets are to be evaluated in stochastic conditions. In order to do this, alternative fleets to the DWO must be generated to be able to detect if other vessel combinations performs better once stochasticity is introduced. This is done as shown in Table 3.8.

Now that a representative collection of fleets has been generated, they are run by the simulation model. The simulation models used for the different cases can be found in Figure 3.3, Appendices C.1 and C.2 respectively. The random seed of which the simulations start is fixed for all fleets, meaning that the induced stochasticity is identical for all the evaluated fleets. This is functional, as the fleets are evaluated on the same grounds. The results of the evaluated fleets in Case 1 are presented in Figure 4.1, while the results of all evaluated fleets for Case 2 and 3 can be seen in Appendices D.1 and D.2 respectively.

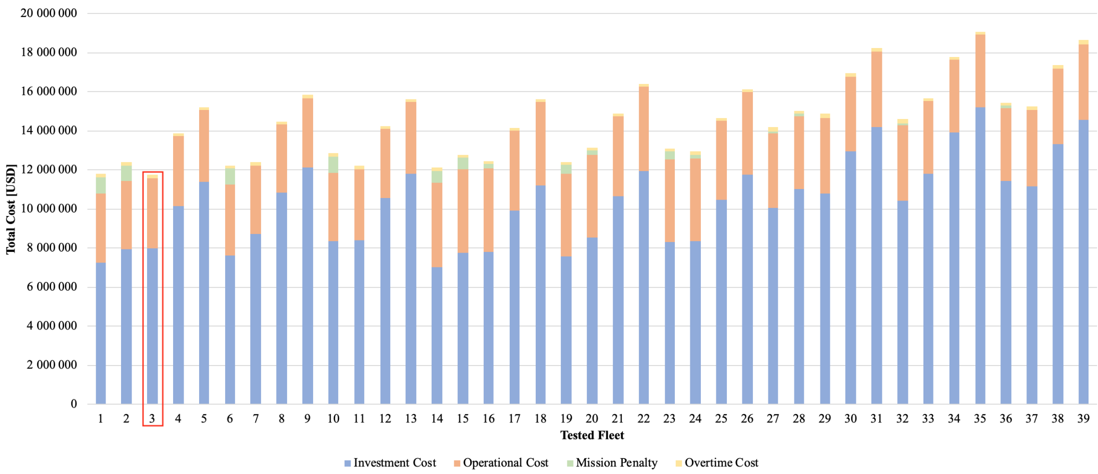

Figure 4.1: Results from the simulations for Case 1

From Figure 4.1, we see that Fleet 3 has the lowest cost, meaning that this is the SWO for the considered case. The SWO for all cases are summed up in Table 4.5.

Table 4.5: The SWO for the presented cases. Green indicates that a new vessel has been added from the DWO, and red represents a vessel that has changed characteristics

Case 1 - Optimal Fleet: 3				**Case 2 - Optimal Fleet: 6**				**Case 3 - Optimal Fleet: 1**			
Cap. [tonnes]	Speed [kn]	OL [-]	Power [kW]	Cap. [tonnes]	Speed [kn]	OL [-]	Power [kW]	Cap. [tonnes]	Speed [kn]	OL [-]	Power [kW]
320	10	3	2115	410	11	4	2473	480	11	4	2752
300	10	2	2035	310	10	3	2075	320	10	3	2115
100	10	2	1367	310	10	3	2075	300	11	3	2120
100	8	2	1238	110	10	2	1411	300	10	3	2035
100	8	2	1238	110	9	2	1332	300	10	3	2035
				110	8	2	1278	300	10	3	2035
				110	8	2	1278	100	11	2	1471
				110	8	2	1278	100	11	2	1471
								100	10	2	1367
								100	10	2	1367
								100	10	2	1367
								100	9	2	1290
								100	9	2	1290
								100	8	2	1238
								100	8	2	1238
								100	8	2	1238
								100	8	2	1238
Total cost [MUSD]			**11.76**				**21.73**				**44.20**

Note that the SWO is not the same fleet as the DWO for cases 1 and 2. This indicates that adjustments to the fleets were beneficial to best endure the introduced stochasticity.

We can also see that the optimal objective value is higher for the SWO than for the DWO for

Case 2 and lower for Cases 1 and 3. The reasons for this will be discussed in Section 5.1.

4.2.2 Deriving the Maximum Value of Emissions and Fish Welfare

As described in Subsection 3.4.1, the next step is to calculate the maximum value of emissions and fish welfare to create the upper bound on costs for the DBO and SBO. The maximum value of reducing emissions is found by testing the simulated fleets from the previous step while applying different combinations of fuel types. This way, we can plot the total cost and the emissions and realize the cost of reducing the emissions by a given percentage. Then, by evaluating the difference in power output and thus emissions between the SWO and a fleet entirely consisting of processing vessels, one can find the maximum unweighted value of emission reductions. Then, this value must be weighted according to the stakeholder interests to find the actual value of reducing emissions.

The tested fleets contain a random combination of the following fuel types:

Table 4.6: Fuel characteristics of the tested fuel types.

Fuel Type	CO_2 [kg/kWh]	Fuel Cost [USD/kWh]	ΔCAPEX [%]
MDO	0.25	0.055	0
LPG	0.22	0.085	5
LNG	0.18	0.01	10
Hydrogen	0	0.285	15

The cost-emission relations for Case 1 can be seen in Figure 4.2.

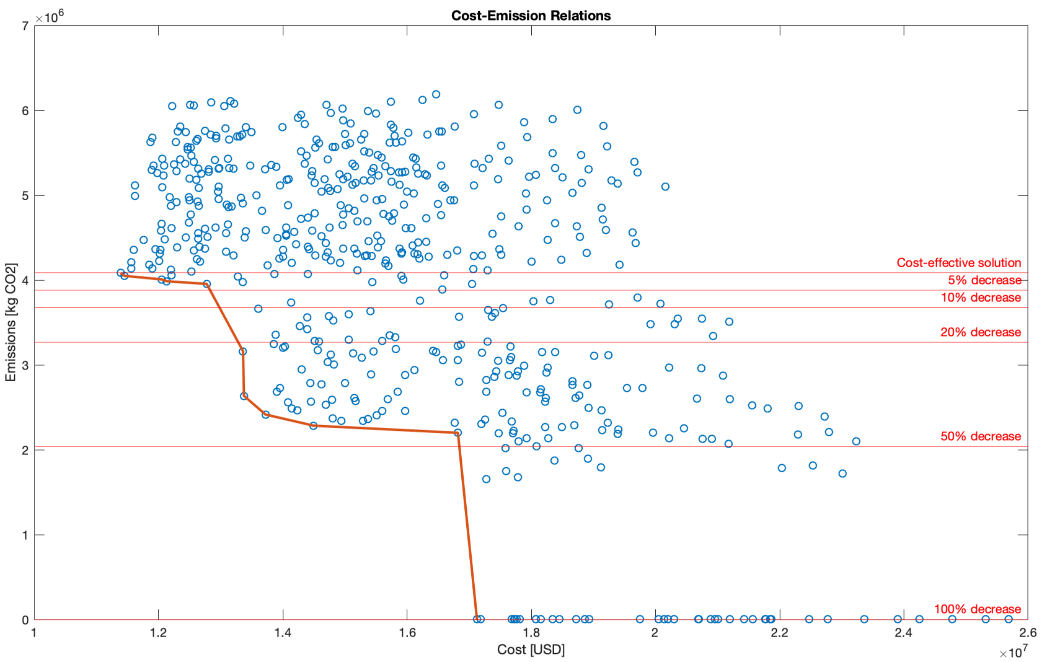

Figure 4.2: Cost-emission relations for Case 1

By linear interpolation between results on the Pareto frontier (red line in Figure 4.2), we can now derive an estimate of the cost of reducing emissions by certain percentages. The cost-emissions plots from the simulations of Case 2 and 3 can be seen in Appendices E.1 and E.2 respectively. A summary of the results is presented in Table 4.7

Table 4.7: The derived cost of emission reductions for the different cases

Emission Reduction [%]	**Cost-Equiv. Value Case 1 [MUSD]**	**Cost-Equiv. Value Case 2 [MUSD]**	**Cost-Equiv. Value Case 3 [MUSD]**
5	1.42	2.61	4.67
10	1.67	2.96	10.02
20	1.92	4.78	10.40
50	5.44	5.85	11.92
100	5.76	9.58	22.58

The SWO for Case 1 has a total installed power of 7993 kW (see Table 4.5). Following the relations derived from the regression analysis (see Appendix A.4), a fleet of processing vessels with the same capacity and speed would have a total installed power of 6797 kW. Thus, the fleet of processing vessels represent a 15% decrease in emissions. By Figure 4.2, the cost-equivalent value of this emission reduction is approximately 1.80 MUSD for Case 1. From the stakeholder analysis in Section 3.3, the true weighted cost-equivalent value of this reduction, and thus the maximum value of emissions is

$$\text{Max Value of Emissions} = 1.80 \cdot \frac{0.072}{0.649} = 0.20\ MUSD = 200\ 000 \text{ USD.}$$

From the proposed method for quantifying fish welfare in Subsection 3.2.1, we look at the quantity of fish transported to find the mortality and damage count. In Case 1, 76 304 tonnes of salmon was transported by the SWO. This gave a cost-equivalent value of 3 090 300 USD, as of Equation 3.1. The corresponding transport by processing vessels would give a cost-equivalent value of 1 335 300 USD. This means that the relative value of transporting the salmon by processing vessels comes to 1 755 000 USD. Now, this value must be weighted by stakeholder interests to find the true maximum value of fish welfare impacts for the given case:

$$\text{Max Value of Welfare} = 1\ 755\ 000 \cdot \frac{0.279}{0.649} = 754\ 500 \text{ USD.}$$

The same procedure is done for Case 2 and 3. The maximum value of emissions and fish welfare is given in Table 4.8.

Table 4.8: The maximum weighted cost-equivalent value of emissions and fish welfare given in USD for the three cases

	Case 1	**Case 2**	**Case 3**
Emissions	200 000	449 500	1 130 500
Fish Welfare	754 500	1 572 200	3 314 300
Sum	**954 500**	**2 021 700**	**4 444 800**

Now the upper bound on costs has been found for the DBO and SBO. For Case 1, no fleet can be optimal if its costs are larger than 11.76 MUSD + 0.95 MUSD = 12.71 MUSD.

4.2.3 Deriving the Optimal Fleet (DBO and SBO)

Now that the upper bound on costs has been included in the optimization model, narrowing the design space, the optimization model is run while including the option of deploying processing vessels. The optimal fleets are presented in Table 4.9.

Table 4.9: The DBO for the presented cases where Cap denotes the vessel's cargo capacity, Sp denotes the vessel speed, OL denotes the vessel's operational limit, P denoted the installed power, Type denotes whether the vessel is a well-boat (WB) or a processing vessel (PV), and WRCEV-E and WRCEV-FW denotes the weighted relative cost-equivalent value of emissions and fish welfare respectively.

Case 1					**Case 2**					**Case 3**				
Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]	Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]	Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]
320	10	3	1649	PV	480	11	4	2018	PV	480	11	4	2018	PV
300	10	3	2035	WB	300	10	3	2035	WB	180	8	2	1327	PV
100	10	2	1367	WB	300	10	3	2035	WB	320	10	3	2115	WB
100	9	2	1290	WB	100	10	2	1367	WB	300	10	3	2035	WB
100	8	2	1238	WB	100	9	2	1290	WB	300	10	3	2035	WB
					100	8	2	1290	WB	300	10	3	2035	WB
					100	8	2	1238	WB	300	10	3	2035	WB
					100	8	2	1238	WB	100	10	2	1411	WB
										100	10	2	1411	WB
										100	10	2	1411	WB
										100	10	2	1411	WB
										100	10	2	1411	WB
										100	10	2	1411	WB
										100	10	2	1411	WB
										100	8	2	1238	WB
										100	8	2	1238	WB
										100	8	2	1238	WB
Inv. Cost				8.43					13.89					28.63
Op. Cost				4.11					7.32					18.61
WRCEV-E				-0.18					-0.35					-0.90
WRCEV-FW				-0.75					-1.39					-2.50
Total Value [MUSD]				**11.61**					**19.47**					**43.84**

Now alternate fleets are designed according to the procedure discussed in Subsection 3.4.7. Next, the fleets are evaluated in the simulation model. The results of Case 1 is shown in Figure 4.3 and the SBO for all cases is given in Table 4.10.

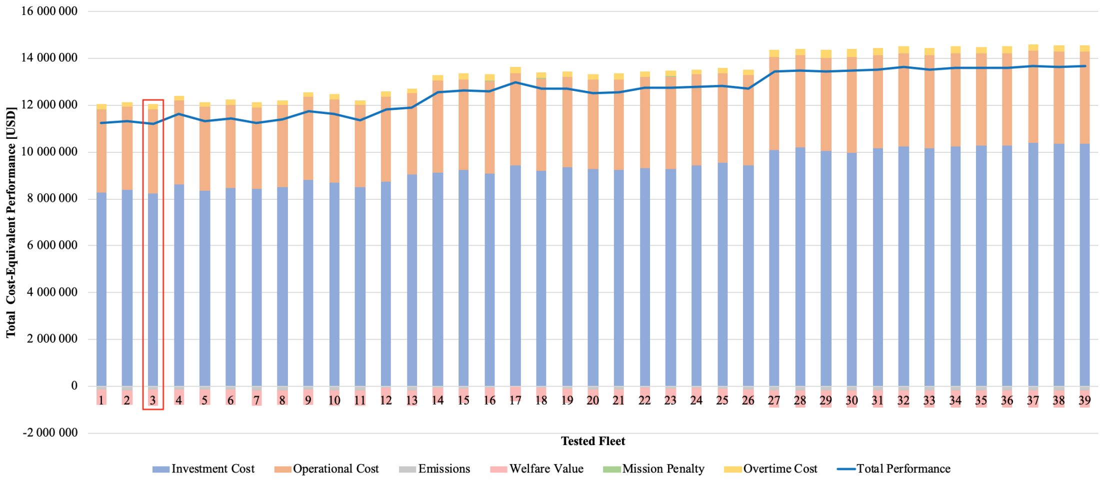

Figure 4.3: The results of the final simulation for Case 1.

Table 4.10: The SBO for the presented cases. Cap denotes vessel cargo capacity, Sp denotes vessel speed, OL denotes the operational limit for the vessel, P denoted installed power and Type denotes whether the vessel is a well-boat (WB) or a processing vessel (PV). The red color represents a vessel that has changed characteristics from the optimal fleet in deterministic conditions

Case 1					**Case 2**					**Case 3**				
Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]	Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]	Cap [t]	Sp [kn]	OL [-]	P [kW]	Type [-]
300	10	3	1603	PV	480	11	4	2018	PV	400	11	4	1834	PV
300	10	3	2035	WB	300	10	3	2035	WB	320	10	3	1649	PV
100	9	2	1290	WB	300	10	3	2035	WB	300	12	3	2247	WB
100	9	2	1290	WB	100	10	2	1367	WB	300	10	3	2035	WB
100	8	2	1238	WB	100	9	2	1290	WB	300	10	3	2035	WB
					100	9	2	1290	WB	300	10	3	2035	WB
					100	8	2	1238	WB	300	10	3	2035	WB
					100	8	2	1238	WB	100	10	2	1367	WB
										100	10	2	1367	WB
										100	10	2	1367	WB
										100	10	2	1367	WB
										100	10	2	1367	WB
										100	10	2	1367	WB
										100	10	2	1367	WB
										100	8	2	1238	WB
										100	8	2	1238	WB
										100	8	2	1238	WB
Inv. Cost				8.23					13.89					29.33
Op. Cost				3.81					7.27					16.97
WRCEV-E				-0.16					-0.28					-0.51
WRCEV-FW				-0.66					-1.18					-2.42
Penalty Cost				0					2.16					0.24
Total Value [MUSD]				**11.22**					**21.86**					**43.61**

4.2.4 Epoch-Era Analysis

As discussed in Section 3.5, it is often useful to consider possible future scenarios when making strategic decisions that affect the company's operations for decades. Therefore, an Epoch-Era Analysis is carried out following the definitions presented in Section 3.5. Each era is presented as a string of epochs, where each epoch has some concrete change that is implemented to the simulation model. The eras, and the corresponding epochs and epoch variables are given by Table 3.9, Table 3.10, and Table 3.11. As seen in Table 3.11, the lifetime expectancy of the fleet is 25 years, and it is assumed that one era defines the changing contexts of this period. Some epochs within the era last longer than others. The simulations are always run for 18 months (one sea-based production cycle), and therefore the performance values for each epoch must be normalized for one-year periods and run through net present value calculations. E.g., the cost-equivalent performance value for an epoch that lasts from the first to the third year of production may be more valuable than an epoch lasting from the sixth to the tenth year although it is shorter, as it is closer in time. Finally, the derived performance for each era is weighted by the determined weights presented in Table 4.3.

The performance of present day simulations and the tested eras is presented for Case 1 in Figure 4.4. The results for Case 2 and 3 can be seen in Subsection G.1 and Subsection G.2. A summary of the optimal performance for each case is presented in Table 4.11.

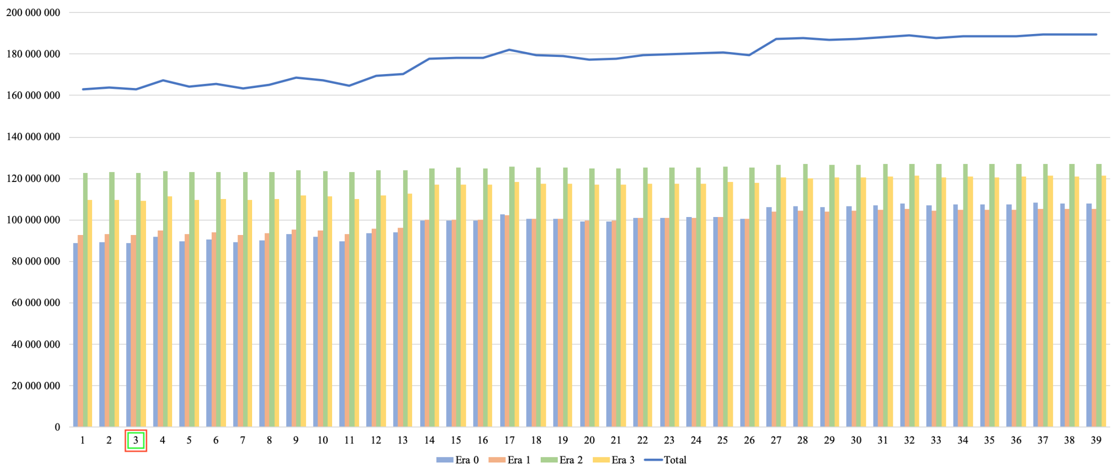

Figure 4.4: The final results for Case 1 with values given by the cost-equivalent performance measure in USD. The red square indicates the optimal solution for the present day analysis and the green square indicates the optimal solution by the Epoch-Era Analysis

Table 4.11: The final results from the Epoch-Era Analysis given by the cost-equivalent performance value in MUSD. SBO denotes the optimal fleet derived from the stochastic conditions and EEAO denotes the optimal fleet derived in the Epoch-Era Analysis.

Simulation	**Case 1**		**Case 2**		**Case 3**	
	SBO	EEAO	SBO	OEEA	SBO	EEAO
Present Day	88.9	88.9	172.7	201.7	347.7	347.7
Era 1	92.7	92.7	175.9	195.7	370.4	370.4
Era 2	122.9	122.9	6 713.7	6 719.4	637.1	637.1
Era 3	109.3	109.3	17 353.8	13 895.6	2 085.2	2 085.2
Total Performance	**163.1**	**163.1**	**5 039.0**	**4 383.4**	**1 003.3**	**1 003.3**

The SBO stayed optimal through the Epoch-Era Analysis for Case 1 and 3 with the applied weights. For Case 2, a more robust solution was found by the Epoch-Era Analysis.

4.3 Evaluation

Three different cases of different sizes were analyzed in the feasibility study in Chapter 4. The number of fish farms was doubled from Case 1 to Case 2 and from Case 2 to Case 3 as well as the locations and sizes of the fish farms being redrawn. The proposed method starts by deriving the optimal fleet of well-boats in a deterministic operating environment (the DWO), and the results can be seen in Table 4.4. The DWO from the different cases included 4, 8, and 17 vessels respectively, reflecting the increasing size of the cases. In Case 1 the DWO involved two vessels of the smallest possible size that largely carried out delousing operations and two larger vessels that carried out salmon transport and delousing operations at fish farms with larger sea states. Instead of implementing capacity restrictions on the delousing operations, e.g. requiring a vessel to have a certain capacity to carry out delousing operations at a given farm, the larger fish farms were assumed to require *more* operations rather than *larger* operations. This was done to represent that large fish farms often have salmon at different sizes that may want different delousing operations. Therefore, the quantity of salmon requiring delousing was assumed to always be smaller than 100 tonnes, meaning that all possible vessels can carry out delousing operations given that the sea state is within the operational limit of the vessel. This assumption may not be very strong for all cases, as some fish farmers may want to delouse more than 100 tonnes of salmon at once. The inclusion of the smallest possible vessel was evident in all tested cases. This is due to these vessels being the cheapest way of carrying out the unconstrained delousing operations. If the list of possible vessels that the optimization model could choose from was to include vessels smaller than 100 tonnes, these would very likely be chosen. This would escalate until a restriction on the necessary capacity for delousing operations was implemented.

From Table 4.5, we can see that the DWO was not optimal in the stochastic and dynamic conditions for cases 1 and 2. As previously stated, the purpose of generating larger alternative fleets was to generate a trade-off between extra investment costs and limited penalty costs. The value of this trade-off is evident in the fact that alterations made to the fleet gave better results for two out of three cases. From Figure 4.1, we can see that the Fleet 3 performs marginally better than the DWO (Fleet 1) for Case 1. It is here evident that the results are very sensitive to how the penalty costs are represented. The penalty costs are simplified in this study, and we can see from Figure 4.1 that if the penalty cost estimates were lower, Fleet 1 would out-perform Fleet 3. The penalty cost estimates evidently has a strong impact on the results and should be carefully considered when applying this method in practice.

We can see from Table 4.4 and Table 4.5 that the total cost of the optimal solutions found in the deterministic and stochastic are similar. One would expect that the total cost in the stochastic environment would be higher, as the induced stochasticity creates sub-optimal routing of the vessels and possibly accumulates penalty costs. However, the rounding error when deciding the required number of missions in the deterministic conditions proved to be significant. For delousing operations, the stochasticity induces a variance resulting in a 10% probability of an extra mission and a 5% probability of cancelling all needed operations. This means that if a fish farm requiring 5 delousing operations in the deterministic, static conditions would have an expected number of operations equal to $5 \cdot 0.85 + 6 \cdot 0.10 + 0 \cdot 0.05 = 4.85$ in stochastic conditions. The same yields for adult transport operations. If the deterministic value of required operations reflected the expected number of operations in the stochastic (real) operating conditions, the total cost in the stochastic environment would very likely prove higher than the one in deterministic conditions.

When deriving the maximum value of emissions, 14 different combinations of the four fuel types presented in Table 4.6 were implemented to the 39 tested fleets and run through the simulation model for each case. The results of the cost-emission analyses (seen in Figure 4.2 and Appendix E.1 and E.2) were reasonable, with lower emissions inducing larger costs. For more accurate results and a stronger representation of the Pareto front, more fuel combinations should be tested. The presented results were, however, found adequate for illustrating its purpose. Interestingly, running the cost-emission analyses revealed a more cost-effective solution than the DWO derived with Marine Diesel Oil. Although the improvements were small, this implies that including fuel type as a vessel characteristic could prove beneficial for improving the overall fleet performance. When deriving the maximum value of fish welfare impacts, the relative cost-equivalent value of transporting the salmon by processing vessels and well-boats was used. A small predicament was, as discussed above, that the transported quantity was somewhat smaller in the stochastic environment than in the deterministic environment. This meant that the maximum value of fish welfare impacts derived from the simulation model could be surpassed in the optimization model. Since the simulation model represents the most accurate depiction of the real events, the maximum value was normalized in the optimization model so that the derived value would not surpass the maximum from the simulation model. This discrepancy could be limited by adjusting the deterministic value for required operations to represent the expected number of missions from the simulation model.

The investment cost estimates from the regression analyses in Appendix A.1 and A.2 are key to the idea of creating a restricting upper bound on costs for the DBO and SBO. The analysis is based on a very small sample size and the investment cost of processing vessels are found to be larger than well-boats for all sizes. If processing vessels were in fact to be found cheaper than well-boats, the upper bound would not be active as the processing vessels would be cheaper in investment and operations as well as better performing within emissions and fish welfare. Therefore, the accuracy of the cost functions are decisive for the proposed upper bound approach having any merit.

After implementing the upper bound on costs, the optimization was run with both vessel types. The results can be seen in Table 4.9. For the results to be valid, the total cost-equivalent performance value would have to be lower or equal to the DWO given in Table 4.4. The DWO serves as an upper bound, as this fleet has been proven to carry out all given missions without including processing vessels. From the results, we see that the total cost-equivalent performance value came at 11.61 MUSD for the DBO, while the total cost of the DWO came at 11.92 MUSD. The fleet performed better after the introduction of processing vessels for all three cases, which confirms that the inclusion of processing vessels produced increased value to the stakeholders in the deterministic analysis.

The results of the evaluated fleets in the stochastic and dynamic operating conditions can be seen in Figure 4.3, Table 4.10 and Appendix F.1 and F.2. As was the case for the well-boats, the optimal objective values from the stochastic conditions were quite similar to the ones found in the deterministic conditions. We can see that for cases 1 and 3, where the penalty costs were small compared to the other factors, the cost-equivalent performance value was smaller in the stochastic conditions. We can also see from Figure 4.3 that the results of the 39 tested fleets deviate less than when deriving the DSO. This implies that the evaluated fleets are more similar in size and composition. This is due to the approach of generating alternative fleets being different. The approach used when considering both vessel types was to gradually cut away small parts of the design space, thus finding alternative combinations optimal for the new situation. This resulted in fleets closer to the optimal fleet in the design space, which consequently resulted in smaller deviations in the design space. This is valuable when the DBO also performs well in the stochastic operating conditions, like for Case 1 (see Figure 4.3). It is less valuable, and may even prove problematic if the DBO performs poorly in the stochastic operating conditions, as the alternative fleets mimic the characteristics of this fleet. As we can see from the results of Case 2, in Appendix F.1, Fleet 1 (the SBO) incurred a penalty cost of over 2 MUSD, making it worse than the SWO. The alternative fleets, which are designed for somewhat rougher conditions but have to stay within the upper bound restriction, were unable to overcome these penalty costs and could not prove valuable when they were needed the most. The results of Case 2 implies that a stronger way of deriving alternative fleets could prove beneficial for the proposed method. A viable option would be to design alternative fleets *after* deriving the performance of the DBO in the stochastic environment. This way, if the DBO accumulates penalty costs, the alternative fleets should be designed significantly larger or routed differently. If the fleet does not incur penalty costs at all, the alternative fleets could be generated on the basis of calmer waters or lower demand for operations, perhaps realizing that the operational conditions were in fact over-dimensioned in the deterministic conditions.

Finally, Epoch-Era analyses were conducted and the results can be seen in Table 4.11, Figure 4.4 and Appendices G.1 and G.2. We can see that the optimal solution found from present day calculations (SBO) remained optimal through the Epoch-Era Analysis for cases 1 and 3. However, for Case 2, a more robust design than the SBO was found. The main purpose of the Epoch-Era Analysis is to derive the most robust fleet by evaluating the fleet's performance under possible future scenarios. The analysis served it's purpose well for Case 1, where the cost-equivalent performance value does not vary as much between the eras. However, for Case 2 and 3, we can see that the cost-equivalent performance values for Era 2 and 3 are much larger than for the present day evaluation. These eras involve increased demand and increased sailing length, which has proven to accumulate large penalty costs for the evaluated fleet. In these situations, the shipowner would likely invest in extra vessels to bode for the increased demand. Thus, the Epoch-Era Analysis as carried out in this thesis does not serve its purpose well for the larger cases when there is no option of investing in additional vessels along the way. If this option was included, the Epoch-Era Analysis should give valuable information on robustness also for the larger cases.

Chapter 5

Discussion

In this section, the proposed method, its assumptions, simplifications and contributions will be discussed.

5.1 Method Foundation

The proposed method of this thesis is based on the collaboration of optimization and simulation tools. The optimization model's task is to derive the fleets to be simulated as well as the routing of the involved vessels. These fleets comprise of the optimal solution in the deterministic condition as well as alternative fleets with certain characteristic similarities. For this to be effective, it is important that the discrepancies between the two model types are minimal so that the fleets derived in the deterministic conditions are likely to be close to the optimal solution for the stochastic conditions.

The main difference between the models is the representation of the sea states and the operation demand. These variables are given a constant, deterministic value in the optimization model, while they vary in the simulation model to best represent the stochasticity of real events. This affects the optimization model's ability to derive the solutions that are most likely to be optimal in the simulation model. An important aspect is how the stochastic variables vary. The simulation model is constructed so that each fish farm needs one extra delousing operation with a 10% probability and that it needs no delousing operations at all with a 5% chance each week. Likewise, each fish farm needs to transport 20% more salmon with a 10% probability and needs no transport operations at all with a 5% chance each week. This means that the deterministic value and the stochastic value will be the same 85% of the time for each operation at each fish farm. For a case involving 10 fish farms and two planned operation types, the models will present the exact same number of operations at each fish farm $0.85^{20} < 4\%$ of the time. The small increase in operations or the exemption from operations during a week has, however, a limited effect on the calculated performance, and the consequential sub-optimal routing of vessels might not have a substantial effect on the overall fleet size and mix problem.

On the other hand, the sea state is very difficult to represent appropriately by deterministic values. As previously discussed, the sea state in the simulation model is calculated from the significant wave height derived from historic data. The sea state varies with the location and the time of year, and may even vary a lot within a single week. The derived sea state is, with a large majority, most often 1, i.e. the calmest operating condition. However, during a period of harsh weather, the sea states may be 4 or 5 for multiple days. The representation of the sea state is important, as the operational limit of a vessel must be as large as the sea state for the vessel to be able to operate. Therefore, if one models the optimization model by the most likely operating condition (sea state 1), the fleet would perform very well for most days, but would not be able to operate at all during other days, which likely would accumulate a considerable penalty cost. On the other hand, if the sea state is over-estimated in the deterministic optimization model, the derived solutions would likely include vessels that are over-dimensioned for the actual operating conditions. The optimal fleet for sea states prone to high variance is likely a fleet with diverse vessels, i.e. some vessels that are designed for calm waters and perform well on most operating days, and some vessels that can withstand rough conditions, and can carry out more operations in periods of harsh weather. To implement this into the optimization model, the different fish farms were given different deterministic sea states. Some of the larger fish farms located further from shore were given a sea state of 3, while most of the other farms were given a sea state value of 1 or 2. This forces the optimization model to include some larger vessels with an operating limit of at least 3 in order to be able to carry out the given missions. Furthermore, since the sea state is the most problematic value to discretize in the optimization model, this is the value that is changed when deriving alternative fleets. This is done to be able to capture a larger part of the design space specifically where the input variables are most sensitive.

Although measures are done to best represent the stochastic variables in the optimization model, this is the main source of uncertainty for the proposed method when it comes to deriving the optimal fleet size and mix. The method does not ensure optimality in a vast multi-dimensional design space, but it derives a high-performing solution with limited computational time based on the characteristics of the optimal solution from deterministic conditions. When introducing stochasticity, the context of the feasible region changes. This means that the global optimum may unveil itself far away in the design space from where the optimal solution was found for the deterministic conditions. This may result in the global optimum being out of reach for the fleets derived from the deterministic environment. However, with the presented method, the performance of the derived solution will not be far off the global optimum as long as the discrepancies between the modelling in deterministic and stochastic conditions are limited.

The proposed method of deriving alternative fleets for simulations is based on a variety of aspects. The main idea of applying optimization and simulation together in this thesis is to limit the number of necessary simulations, and thus limit computational time. Ideally, all possible fleet compositions would be simulated, but this would require a simulation time surpassing the expected lifetime of the fleet. When deriving the optimal fleet in the deterministic environment, we are already somewhat aware of how the induced stochasticity will affect the fleet's performance. Since it was considered likely that it was more beneficial that vessels on occasion stay in port without a mission rather than the fleet not being able to complete their missions, the majority of the alternative fleets were chosen to be subject to harsher deterministic conditions, in order to possibly over-dimension the fleet and reduce the risk of accumulated penalty costs. Since the design options are plentiful, encircling a complete region in the design space with significant alterations to the optimal fleet was not found feasible with regards to computational time. Therefore, alternative fleets were generated as points in the design space with some distinct similarity to the optimal fleet. This method of designing alternative fleets becomes decreasingly functional as the design space grows, i.e. it is much more difficult to represent the optimal region with pinpointed designs in a vast multi-dimensional problem than in a small two-dimensional problem. A possible improvement of this approach could strengthen the method, and might include deriving the alternative fleets *after* deriving the results of the DWO/DBO in stochastic conditions. Hence, the information gathered from these results could be utilized to make informed decisions on the design of alternative fleets. Designing some alternative fleets for a larger demand could also be interesting as a safety margin for induced extra missions. E.g. it could be beneficial for the largest vessel in the fleet to have a capacity of 580 tonnes although the largest demand for adult transport on a normal day is 480 tonnes, as the induced stochasticity of 20% demand increase would still be within the capacity of the vessel.

When carrying out strategic planning, it is often problematic to capture the effect of the underlying tactical and operational planning problems. The consequences of this is evident, especially in the simulation model. From the optimization model, the fleet size and mix is derived as well as the optimal routing for the given input parameters. The routing serves as a basis for the routing decisions to be made in the simulation model, but will not be accurate, as the number of necessary missions and sea states differ from the optimization model. As presented in Subsection 3.4.3, the routing decisions unique to the simulation model is evident when a vessel cannot operate at its intended fish farm on a given day or when a vessel has carried out all its designated missions and can offload other vessels of their missions or carry out extra missions induced by variance. The routing decisions implemented into the simulation model are made as reasonable as possible, e.g., if a vessel cannot operate at the intended fish farm, it should attempt to carry out one of its other designated missions or if a vessel has carried out its missions, it should attempt to offload another vessel to limit penalty costs. However, as the conditions change from week to week, the routing decisions made will rarely be optimal. This is likely to have a significant impact on the final results and should be taken into consideration. The implementation of a routing heuristic in the simulation model could be useful to make better routing decisions. The routing of vessels could then be done at the start of each week, when acquiring new missions, possibly by considering a one-week weather forecast to incorporate the operational planning problem into the routing problem.

The extent to which the simulation model is able to catch all relevant impacts on the fleet is important to accurately represent the fleet's performance. The effects of the simplifications and basic assumptions made should be evaluated before deeming the results as representative for real events. Several simplifications were made in this thesis that may affect the results. It was assumed that the vessels' speed represents the average service speed for the vessel during sailing, and that this was never altered. Further, speed reductions due to rough sea states were not included. This would increase operational time and possibly induce overtime costs and increased operational costs. Further, some basic assumptions were made with regards to the fish farmers' production strategies, e.g. all juvenile transport being done in the first week of operations. This is, however, accounted for to some extent by considering the adult transport to be done for 25 weeks, representing a quite diversified production. Each fish farmer's production strategy and operational preference is individual and the simplifications made will therefore not accurately represent all possible conditions. However, the assumptions made on production strategies are based on common practice, and were assumed functional for the objective of the work. Albeit, the option of different delousing operations, separate sorting operations, lice counting operations and other maintenance and repair related operations that well-boats may perform were not included. This, along with more accurate estimates of the operating time for the different operations, would improve the accuracy of the results.

The discussed performance parameters are based on recent focus areas in the industry. Cutting emissions as well as improving fish welfare is widely discussed without much concrete action being taken. This may be a result of the fact that weighting models for evaluating emissions and fish welfare against costs are scarce or in fact non-existent. Furthermore, the distinct quantification of these aspects into functional performance parameters has been lacking. The proposed quantification of emission reductions is quite strong, as simulations with different fuel types were carried out to evaluate the increased costs of emission reductions. Although carrying out further simulations with more combinations of fuel types for each vessel in each fleet would strengthen the quantification further, the analysis made in this thesis is considered adequate for the feasibility study. The quantification of fish welfare is, as previously discussed more complex. The literature on fish welfare is abundant, but specific analyses on the fish welfare impacts of different operations relevant for well-boats and processing vessels has not been carried out. The impact of low fish welfare on the fish farmer's reputation and the consequences of this is also a large part of this quantification where thorough analysis is lacking. Therefore, the proposed quantitative representation of fish welfare is a simplified estimation. If more abstract aspects of the salmon life cycle like fish welfare are to be implemented into decision-making, thorough analysis should be done on welfare impacts and their effects on fish farmers and the industry.

To bode for the simplified quantification of the performance parameters, a stakeholder analysis was performed as a proposed method of grasping how highly the stakeholders *actually* evaluate the performance parameters. This will always be unique to each group of stakeholders, their business strategy and their values. However, by performing a stakeholder analysis, the stakeholders can consider the proposed quantification and decide to what extent they agree with the evaluations presented. The stakeholder analysis was simplified to consider all involved stakeholders as a united group with a common voice. This is not typically the case in real decision-making processes, where decision-making typically comprise of bargaining, leveraging and compromises. The Analytical Hierarchy Process was applied to quantify the stakeholders' evaluation of the performance parameters based on their pair-wise preference. This can be extended to also deriving the influence of each stakeholder on the decision-making process, thus weighting the stakeholder's evaluation of the performance parameters by its influence on decision-making. This might give a more holistic understanding, although deriving what stakeholder has the largest influence on decision-making may be even more complex than deriving their evaluations of the performance parameter. Albeit, constructing concrete performance parameters that surpasses solely considering costs and involving these in decision-making, gives the stakeholders insight into how making strategic design decisions can create value further than by limiting costs.

Scenario planning was implemented into the proposed method as a way of evaluating the robustness of the fleet designs and incorporating this aspect into decision-making. Epoch-Era Analysis was used for scenario planning where epochs and eras were constructed based on possible future contexts. The analysis was simplified somewhat for this thesis, limiting the number of considered epochs and eras. Furthermore, the implemented changes and their impacts on operations were reduced to only the aspects already considered in the thesis, e.g. for the possible future change of fish farms moving offshore, changes to the fish farm size, sailing distance and sea state were implemented, but impacts like more complex and time-consuming operations, possibly with different equipment was not considered. This was neglected mainly to constrain the scope of the thesis, but also due to the lack of insight into the complexity of the implemented changes. When constructing eras, a narrative approach was used, i.e. basing eras on what future contexts the stakeholders believe are likely to happen. This approach is subjective and may reflect the biases of the stakeholders, allowing eras to be based solely on wishful thinking. A more thorough computational and probabilistic approach could prove valuable, but as the proposed method of this thesis already is based on the stakeholders' subjective evaluations through the stakeholder analysis, a subjective narrative approach was found sufficient.

5.2 Method Applicability

The principle of the proposed method is to introduce a more holistic way of solving strategic planning problems by capturing the most relevant performance parameters in the Norwegian aquaculture industry. The method is, however, fruitless if it is not pertinent to the main actors of which the method is aimed at. The shipowners and the fish farmers in the Norwegian aquaculture industry have been highly profitable for the past few decades, which consequently has brought significant slack in important decision-making situations. Since the actors do not have to go out of their way to turn a profit, strategic decisions like fleet size and mix problems or vessel acquisitions have a tradition of being made on gut-feelings and past experiences rather than on computational analyses. Some actors are still prone to the attitude of thinking that what they are doing is working really well so why bother changing things. This is considered to be the largest entry barrier of the proposed method, i.e. actors not being interested in improving their strategic decision-making.

As previously stated, most shipowners have a fleet of vessels with different ages so that the entire fleet does not have to be changed all at once. Although there may still be situations where a complete fleet acquisition or renewal is desired, with the most common situation being a new actor entering the industry, this means that optimizing the acquisition of single vessels to be added to the current fleet could be more relevant to the actors in the industry. The option of adding single vessels to a current fleet could also be suitable for scenario planning, where instead of designing a fleet that may be sub-optimal in the current conditions to increase robustness, one may want to design the fleet to optimality in the current situation with the planned option of adding on vessels later on if or when concrete changes to the operating conditions happen. The proposed method can be applied for adding single vessels to a current fleet by simply constraining the fleet size and mix problem to including the vessels currently in the fleet and thus optimizing the vessel characteristic of the required additions.

A possible predicament for the proposed method is that it relies on accurate representations of abstract aspects of operations. For the method to be able to distribute accurate representations of what the stakeholders value, the stakeholders must be able to quantify their preferences, i.e. by deriving accurate representations of the cost-equivalent values of the performance parameters or by compiling weighting averages that represent their evaluation of the performance parameters. This may be easier in theory than in practice, as the decision-making processes in strategic planning problems traditionally are done either by gut-feeling or is prone to bargaining or compromises. However the stakeholders choose to weigh the considered performance parameters, the proposed method is functional, e.g if the stakeholders decide that they only care about costs, a weight of zero for all other performance parameters would result in the most cost-effective result being derived. The upper bound approach would then be irrelevant, and deriving the optimal fleet of only well-boats would be superfluous. Furthermore, stating that fish welfare has zero importance would be problematic, as the fish welfare quantification include both direct and indirect costs. Therefore, not considering fish welfare at all would be saying that the direct costs of salmon mortality has no effect on the generated value for the stakeholders. In retrospect, it could be reasonable to include only the indirect costs in the performance parameter for fish welfare, but then again, the reduction in direct costs from better welfare would not be reflected in the performance parameter.

In theory, there is no bound on the size or complexity of the problems that can be solved by the proposed method and with the designed models. However, better modelling to minimize the discrepancies between the optimization and simulation models becomes increasingly important as the problem size increases. If discrepancies are limited, complex and detailed inclusions to the problem can be included as long as it can be quantified.

A relevant extension in keeping with the industry today is the inclusion of PD-zones, i.e. zones with special regulations with regards to limiting the spreading of pancreatic disease among fish. In these zones, special regulations apply, like all transport having to be done with closed compartments. Farms located in such areas may also be more prone to fish saving operations and require less delousing operations. If one can quantify these effects, the inclusion of PD-zones can easily be incorporated into the models. Therefore, extensions to the models to better fit the real operating conditions are unproblematic as long as one can quantify the relevant impacts on the fleets overall performance.

5.3 Contributions

In Section 1.2 the contributions of the thesis were stated. The fulfilment of these are discussed below.

Determine common practice of strategic planning and fleet design in aquaculture: The state of the art of strategic planning and fleet design in Norwegian aquaculture was presented in Section 2.4 and Section 2.5. Strategic planning in the industry is usually based on past merit and the decision-maker's experience rather than computational methods, which can result in shipowners making sub-optimal decisions. This leads to shipowners missing out on value. Furthermore, fleet design is rare in the industry, as shipowners often acquire single vessels to continuously update their fleet rather than making complete fleet renewals.

Quantify the stakeholders' value factors into functional performance parameters: The stakeholders core values were determined as being costs, emissions and fish welfare. The quantification of these value factors into functional performance parameters was done in Section 3.2. This comprised of deriving cost-equivalent performance values for emissions and fish welfare so that the fleet's performance within these aspects could be quantitatively compared to the cost estimations. The cost-equivalent value of emission was derived through simulations of fleets with different fuel combinations, resulting in cost-emission relations that indicated the added cost of reducing the emissions of the fleet. Fish welfare was quantified by considering direct and indirect costs of damages and fatalities to the salmon. The direct cost was related to the loss of product while the indirect cost was related to reputational damage.

Derive the stakeholders' evaluations of the performance parameters: The stakeholders' evaluations of the described performance parameters were derived through a stakeholder analysis in Section 3.3. By the use of the Analytical Hierarchy Process, the pair-wise evaluations of the performance parameters resulted in weighting averages that would later be used for deriving what the *actual* value of the performance parameters are considering the stakeholders' incentive to invest in performance enhancing measures.

Propose a method for solving maritime fleet size and mix problems: The proposed method for solving maritime fleet size and mix problems was presented in Section 3.4. The method applies optimization and simulation models in collaboration to utilize the strength of the two model types. The optimization model describes a deterministic operating environment where all input variables are constant. The optimal fleet derived from these conditions, along with generated alternative fleets with similar characteristics, are evaluated in the simulation model. The simulation model presents stochastic operating conditions more depicting of the real world. Here, input variables, like the demand for operations and the sea states, vary. The optimal fleet was derived as the fleet with the lowest cost-equivalent performance value.

Design optimization models for deterministic conditions using FICO Xpress: The construction of the optimization models was described in Subsection 3.4.3. The optimization model was designed to derive the fleet with the lowest cost-equivalent performance value based on a list of vessels that the model could choose from to include into the fleet. The model was also set to derive the optimal routing of these vessels given a set of fish farms with their sizes and locations, and a list of missions to be carried out. The models solved the fleet size and mix and routing problems using integer programming, and produced realistic results for the tested cases in Chapter 4. The models are available as attachments to this report.

Design simulation models for stochastic conditions using MATLAB SimEvents: The construction of the simulation models is described in Subsection 3.4.5. These were designed to better represent the dynamics and variance in real events. The model was used as a tool to evaluate the derived fleets from the optimization model, and present the fleet with the best performance in the described operating conditions. The models produced realistic results for the tested cases in Chapter 4. The models are available as attachments to this report.

Implement scenario planning into design decisions using Epoch-Era Analysis: The implementation of scenario planning in the form of an Epoch-Era Analysis was presented in Section 3.5. The applied epochs were based on possible future changes to the operating contexts and the eras were designed to represent a logical string of epochs. The results of the analysis can be seen in Subsection 4.2.4. The Epoch-Era Analysis was found purposeless for the larger test cases without the option of adding vessels to the fleet when it would seem reasonable to do so, e.g. with higher demands or longer sailing distances.

Verify and validate the decision-support system through a feasibility study: The results of the feasibility study can be seen in Chapter 4. The decision-support system derived realistic results for all three test cases. The optimal fleet for all three cases included both well-boats and processing vessels. The feasibility study, under the assumptions and simplifications made, therefore implies that there is merit to quantitative strategic planning in the industry, as combining vessel types in the fleet is uncommon for shipowners in the Norwegian aquaculture industry.

Chapter 6

Conclusions and Further Work

The proposed method and the designed decision-support system derived realistic results based for the tested cases in the feasibility study. By the implementation of a wider definition of fleet performance and the quantification of performance parameters surpassing costs, the system allowed stakeholder to weight the importance of the value factors affecting their operations and base strategic decisions on this. The decision-support system proved the value of strategic planning, as the derived optimal fleets included both well-boats and processing vessels for all tested cases, which is not common in modern fleets.

There are still several improvements that can be made to strengthen the proposed method. As discussed, improving the method for generating alternative fleets to be evaluated in the stochastic environment would increase the probability of approaching the global optimum in the stochastic conditions.

Furthermore, to limit the discrepancies between the optimization and simulation models, including a routing heuristic in the simulation model could be beneficial. Instead of basing routing decisions on what was optimal in the deterministic conditions, the fleet could be routed upon deriving the weekly mission list in the simulation model and by considering a one-week weather forecast. This would provide more accurate performance evaluations.

To derive more accurate results, a better understanding of the required operations, i.e. sizes and frequencies, is required. Furthermore, more holistic, quantitative research on fish welfare impacts during operations and the effect of these impacts on the fish farmer's reputation and general operation, would lead to a more accurate quantification.

Despite the shortcomings and possibilities for further work discussed above, the work conducted in this thesis is considered successful. The main goal of the study has been to propose a unified model for getting a (close to) optimal solution to the fleet size an mix problem, and the feasibility study indicates that this goal has been reached.

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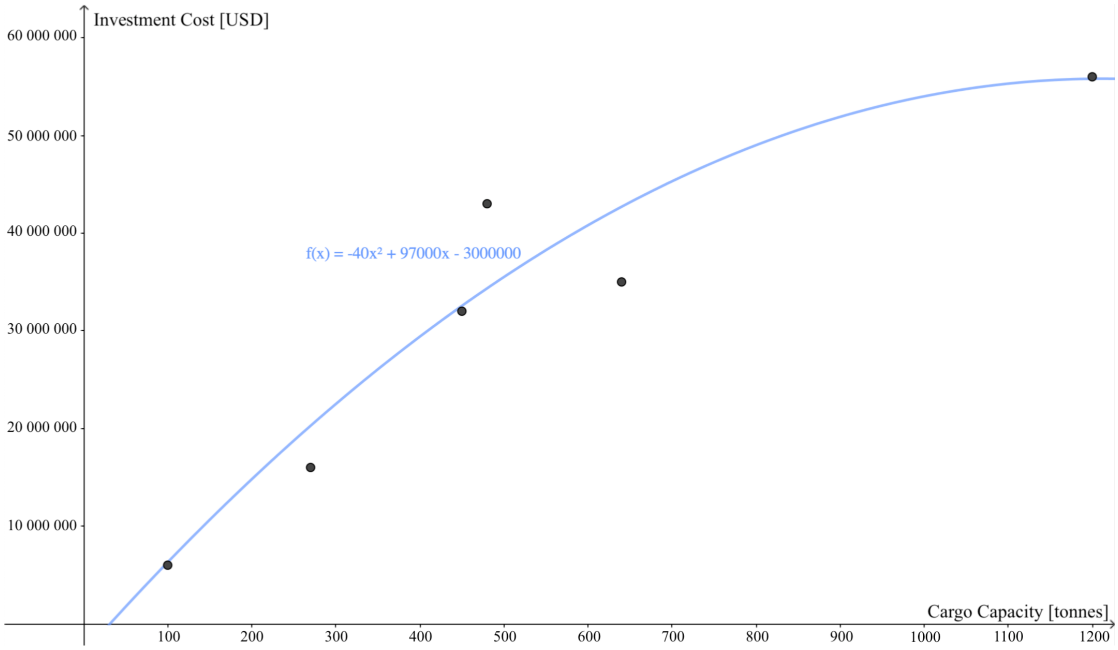
Appendices

A Regression Analysis for Deriving Vessel Characteristics

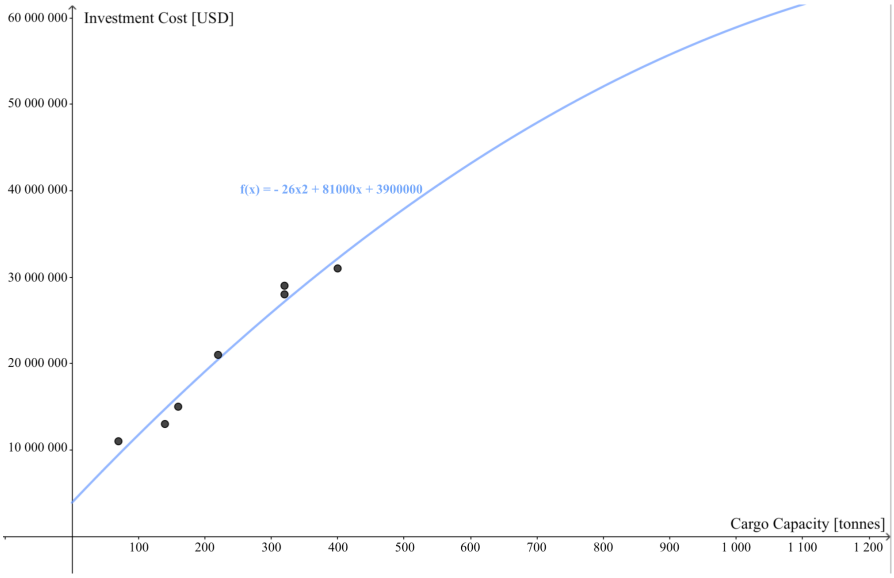
A.1 Investment Cost by Cargo Capacity for Well-boats

Figure A.1: The investment cost in [USD] given as a function of the cargo capacity in [tonnes] for well-boat newbuilds



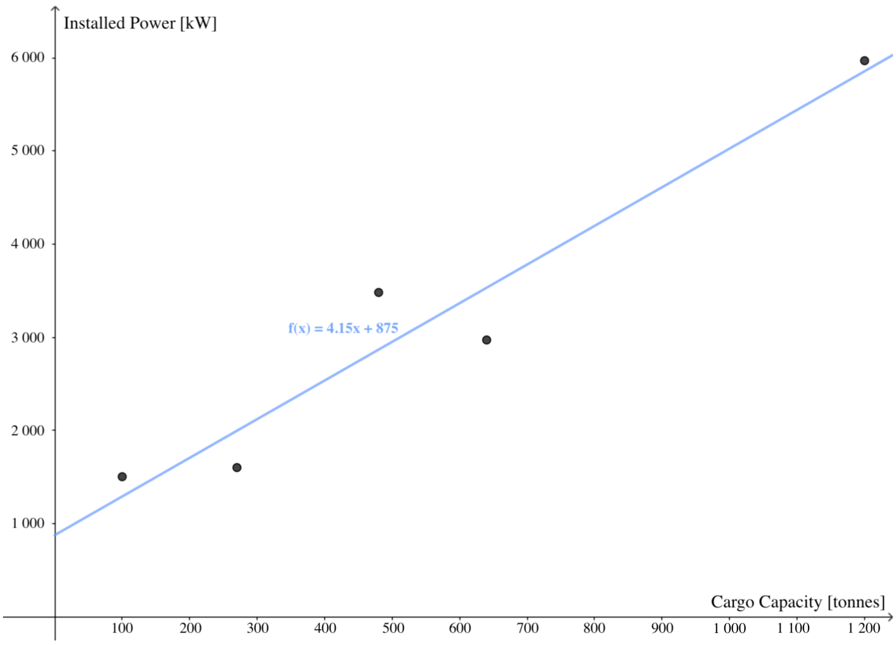
A.2 Investment Cost by Cargo Capacity for Processing Vessels

Figure A.2: The investment cost in [USD] given as a function of the cargo capacity in [tonnes] for processing vessels



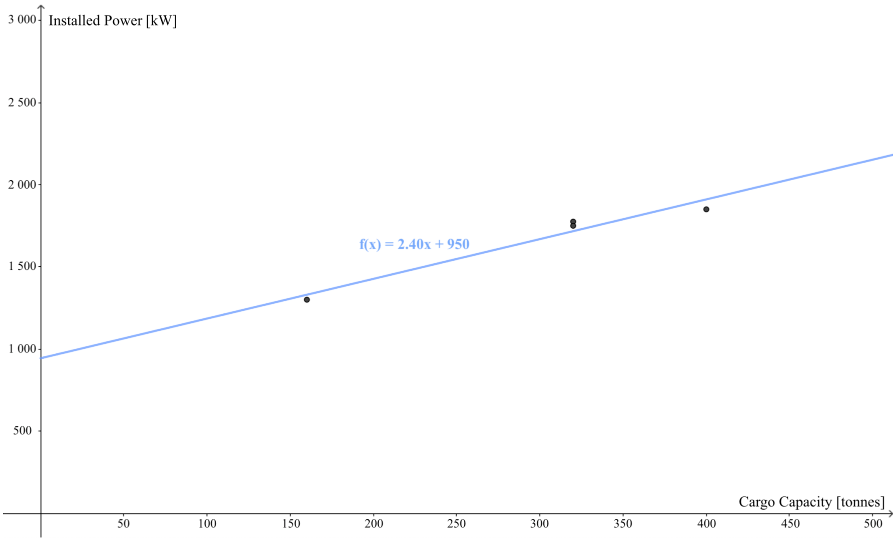
A.3 Installed Power by Cargo Capacity for Well-boats

Figure A.3: The installed power in [kW] given as a linear function of the cargo capacity in [tonnes] for well-boat newbuilds



A.4 Installed Power by Cargo Capacity for Processing Vessels

Figure A.4: The installed power in [kW] given as a linear function of the cargo capacity in [tonnes] for processing vessels



B Fish Farm Size and Location

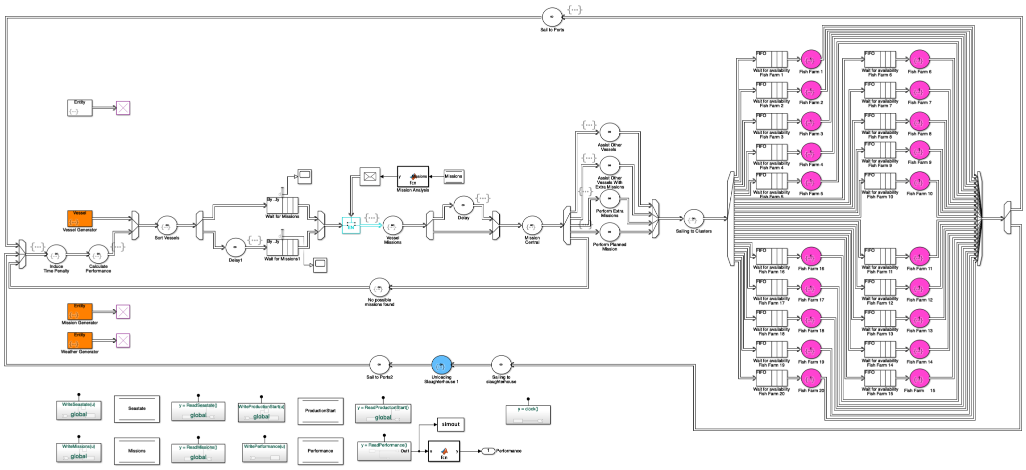
Table B.1: The fish farm sizes and locations. D1 denotes the round-trip from port to hatchery to farm and back to port, D2 denotes the round-trip from port to fish farm and back to part, and D3 denotes the round-trip from port to fish farm to slaughterhouse and back to port.

	Case 1				**Case 2**				**Case 3**			
Farm	Size	D1	D2	D3	Size	D1	D2	D3	Size	D1	D2	D3
1	12	64	60	62	12	70	58	60	12	20	18	22
2	10	56	50	52	12	20	14	16	12	30	24	36
3	10	50	46	48	12	56	46	50	12	56	54	54
4	10	12	10	12	12	14	6	8	12	34	28	40
5	8	42	36	40	10	28	8	12	12	6	4	4
6	8	32	30	32	10	66	56	58	12	40	38	38
7	8	20	16	18	10	34	30	32	12	72	52	66
8	6	58	54	56	10	42	40	40	12	62	56	60
9	6	36	32	34	10	16	10	10	12	42	42	42
10	4	28	20	30	8	22	22	24	12	58	40	52
11					8	64	40	46	10	24	24	28
12					8	52	46	48	10	64	48	60
13					8	10	6	12	10	42	34	48
14					8	18	12	18	10	42	36	38
15					8	62	60	60	10	44	44	48
16					6	30	24	26	10	14	14	16
17					6	56	42	48	10	70	70	72
18					6	8	8	14	10	80	74	80
19					4	18	14	16	10	74	48	78
20					4	46	42	42	10	76	76	82
21									10	80	76	84
22									8	64	60	64
23									8	44	24	38
24									8	72	50	70
25									8	24	20	26
26									8	54	46	56
27									8	4	4	4
28									8	12	8	10
29									8	48	46	54
30									8	6	4	6
31									8	16	8	14
32									8	44	42	48
33									6	62	58	58
34									6	80	76	76
35									6	4	4	6
36									6	36	32	34
37									6	72	66	74
38									4	44	40	40
39									4	32	26	28
40									4	28	16	26

C MATLAB SimEvents Model Used for Simulations

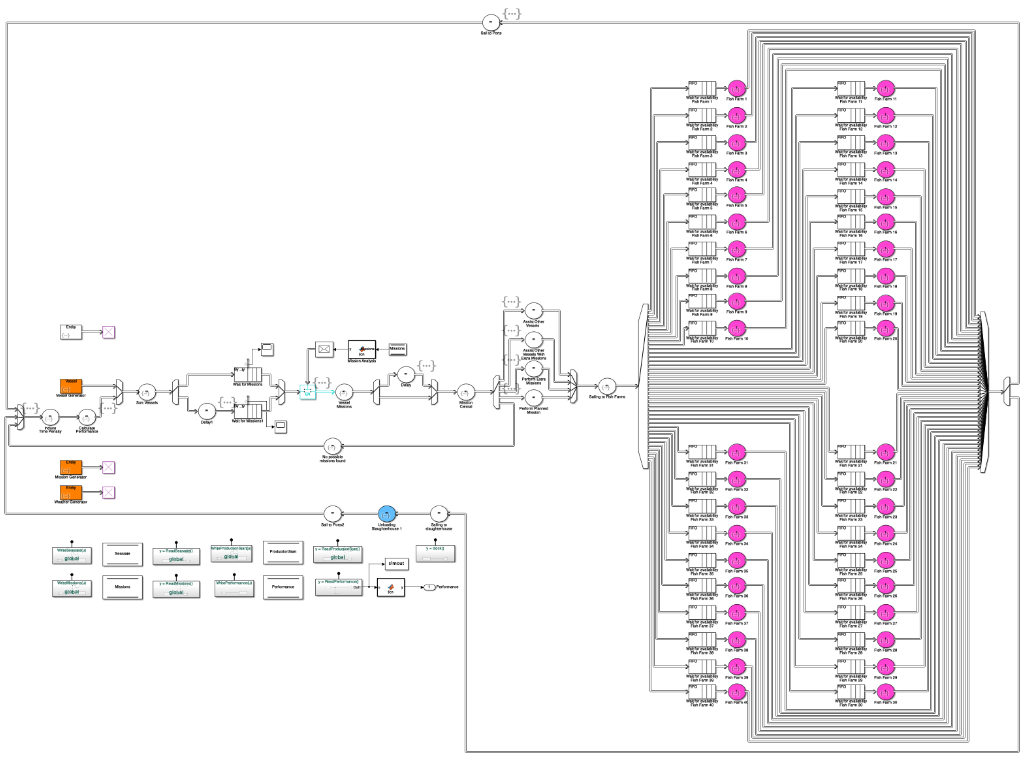
C.1 Case 2

Figure C.1: The simulation model used for Case 2



C.2 Case 3

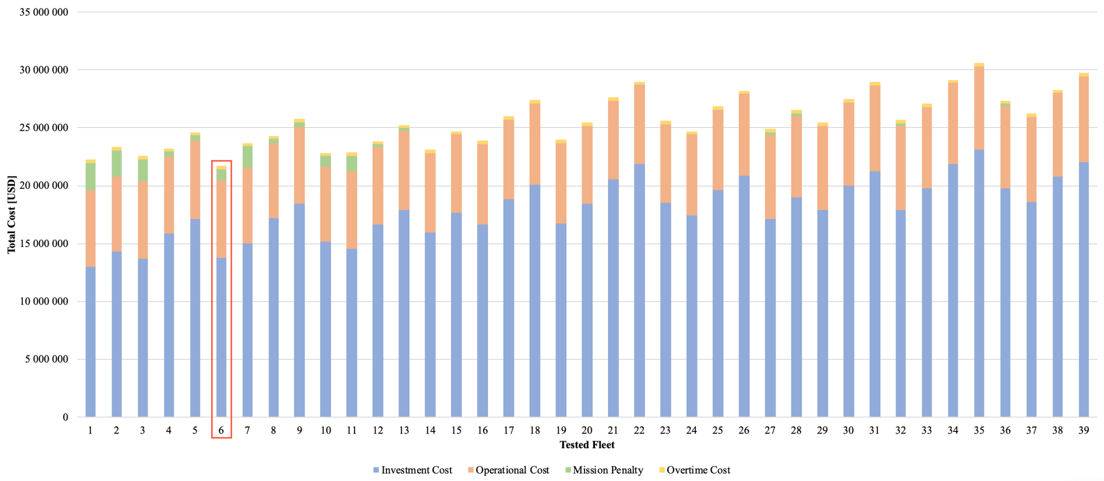
Figure C.2: The simulation model used for Case 3



D Results of All Simulated Well-Boat Fleets

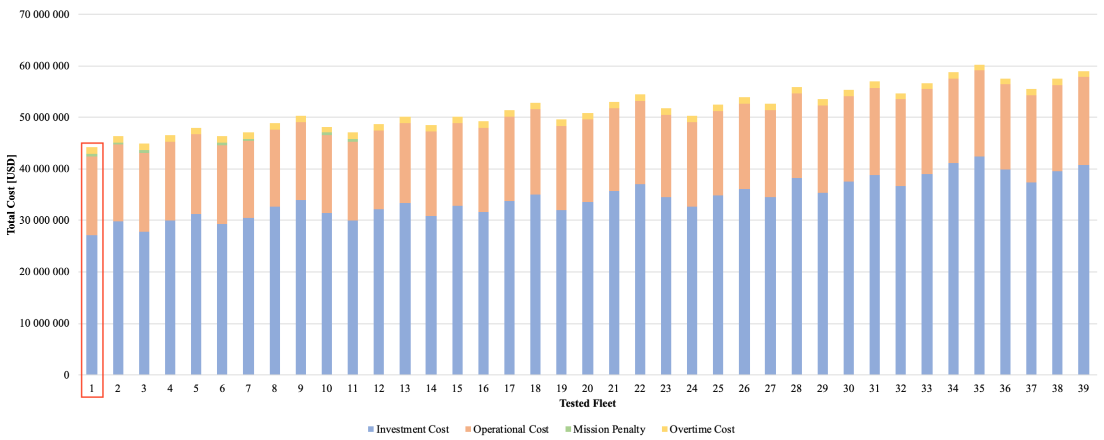
D.1 Case 2

Figure D.1: The results from the simulated fleets of well-boats in Case 2 given by the cost-equivalent performance value in [USD]



D.2 Case 3

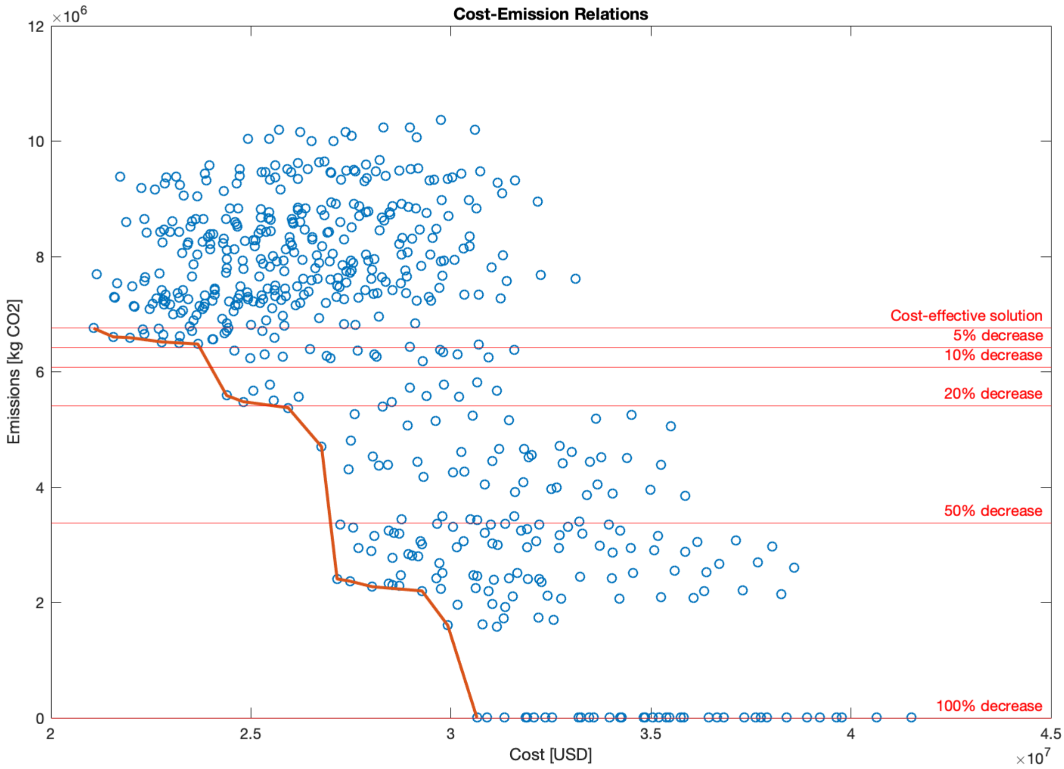
Figure D.2: The results from the simulated fleets of well-boats in Case 3 given by the cost-equivalent performance value in [USD]



E Cost-Emission Relations

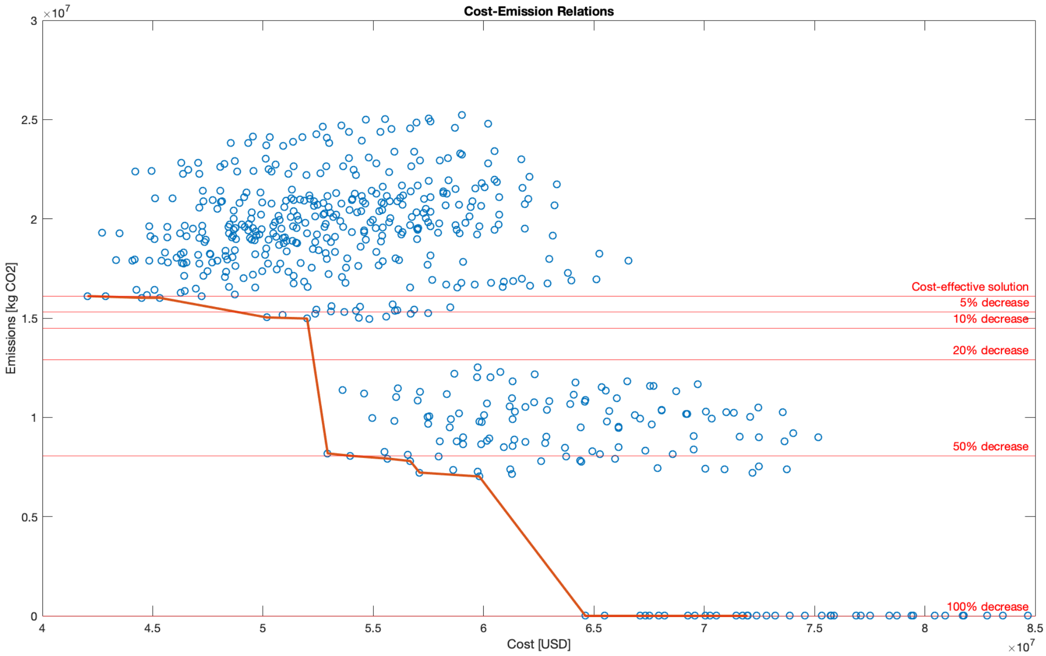
E.1 Case 2

Figure E.1: The cost-emission relation derived from Case 2, given by CO_2-emission in [kg] and total cost in [USD]



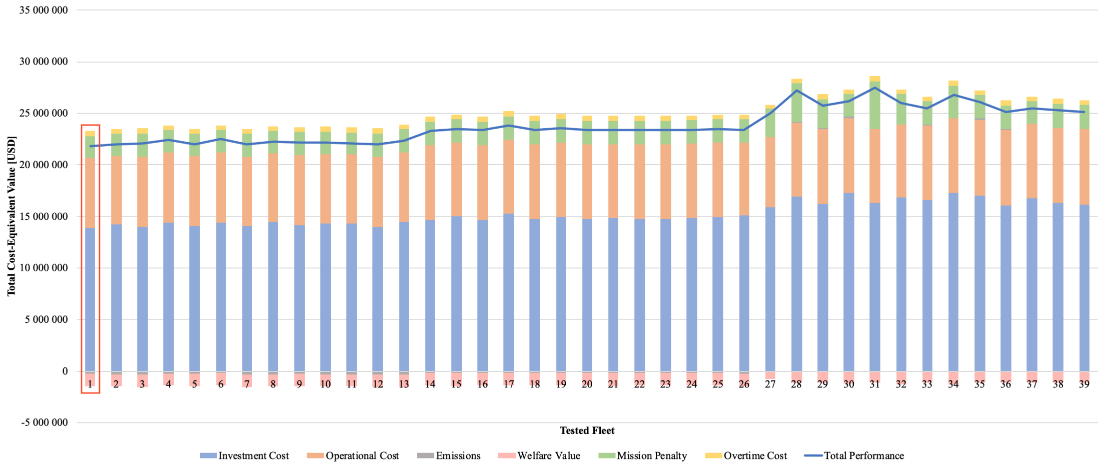
E.2 Case 3

Figure E.2: The cost-emission relation derived from Case 3, given by CO_2-emission in [kg] and total cost in [USD]

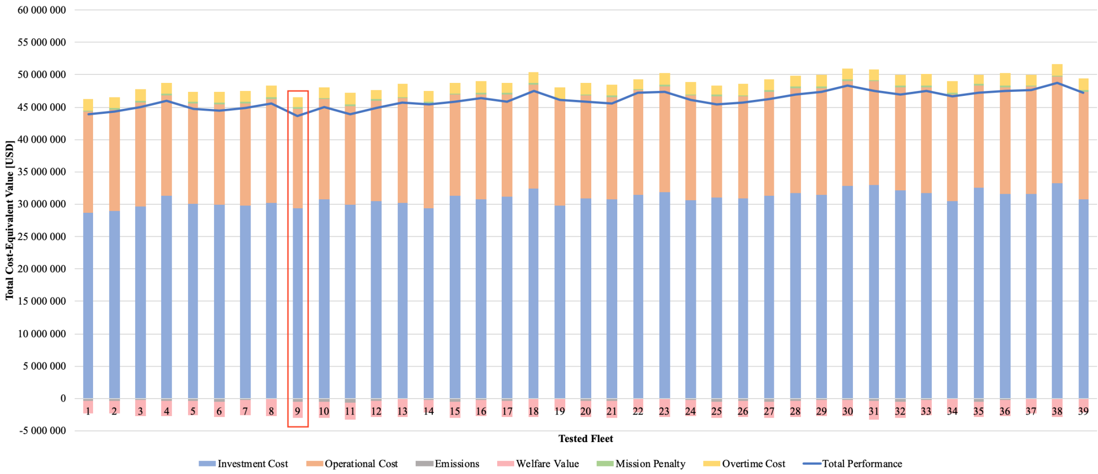


F Results of All Simulated Fleets

F.1 Case 2



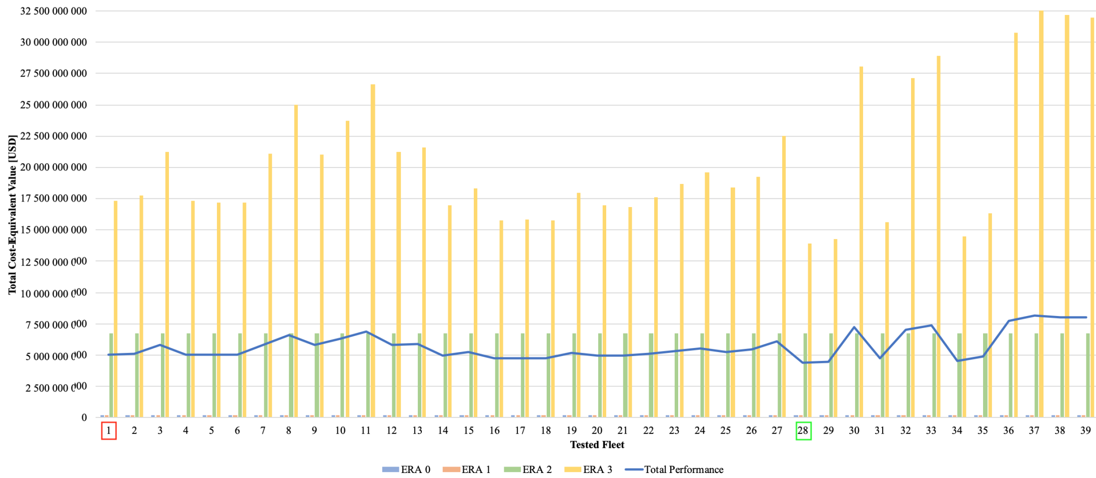
F.2 Case 3



G Results from the Epoch-Era Analysis

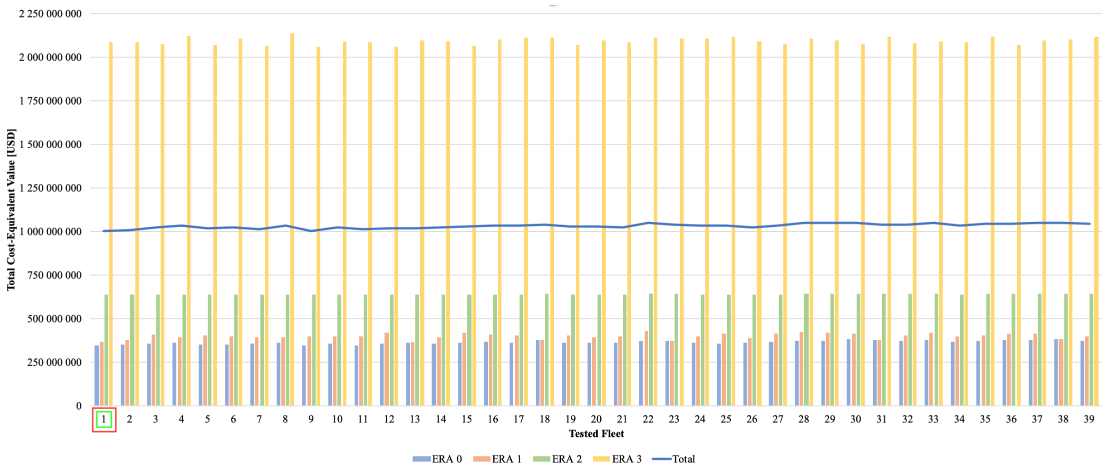
G.1 Case 2

Figure G.1: The results of the Epoch-Era Analysis of the simulated fleets from Case 2 given by the cost-equivalent performance value in [USD]



G.2 Case 3

Figure G.2: The results of the Epoch-Era Analysis of the simulated fleets from Case 3 given by the cost-equivalent performance value in [USD]



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