Technical Challenges and Benefits of Integrating Atlantic Salmon Production in Floating Offshore Wind Farms

A conceptual design study

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In cooperation with Hexicon AB

TU Delft

S.P.J. Verschoof

Technical Challenges and Benefits of Integrating Atlantic Salmon Production in Floating Offshore Wind Farms

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by

S.P.J. Verschoof

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Cover photo courtesy: Hexicon AB (top), Marine Harvest (bottom)

Abstract

Multi-use of offshore platforms is a long-term research challenge which aims to combine food and energy production at sea. Research in this field is in its infancy, literature is scarce and without much cross-referencing. The aim of this thesis has been to develop a coherent set of recommendations for the further development of multi-use platforms, specifically for offshore floating wind energy and salmon aquaculture.

A design-oriented approach has been adopted to generate insights regarding multi-use platforms. New multi-use concepts were generated and presented, illustrating what a future multi-use farm could look like. Simultaneously, a rigorous decision-making framework was set-up aimed at identifying superior concepts, while systematically producing insights by making explicit the trade-offs which govern the decision. A most preferred concept has been selected and evaluated in more detail, focussing on the identification of engineering challenges and cost-reduction opportunities through comparison of the multi-use concept with stand-alone references.

Except for one item, no major technical barriers for the further development of multi-use platforms were identified, given that the challenges associated to the stand-alone activities can be met. This item is the expectation that mooring loads will largely increase by integrating fixed-netting structures in wind energy platforms.

A small set of cost-reduction opportunities was discovered, as well as threats to the economic viability. Evaluation of the cost-reduction potential nuanced the view that large opportunities exist in mooring design and shared O&M vessels and demonstrated that the multi-use concept can also lead to additional costs. Most importantly, further study into the availability of optimal sites for multi-use is recommended, because it can be expected that sites optimal for wind energy may be sub-optimal for the production of Atlantic Salmon.

Acknowledgements

First of all, I am thankful to Delft University of Technology and the Wind Energy research group in particular for giving me the opportunity to carry out this research on a subject of my own choosing. My gratitude extends to Hexicon AB for welcoming me as research intern. Although all errors of fact and judgment are exclusively my own, I should like to acknowledge with sincere gratitude those persons who assisted me in drafting this thesis.

Foremost, I am deeply grateful to my daily supervisor Dr. Michiel Zaayer whose accessibility, sense of humour and detailed criticisms inspired, stimulated work ethic and greatly improved this thesis. Moreover, I would like to thank Prof. Simon Watson for chairing my committee and ir. Frank Sliggers for reviewing this thesis as external committee member. I am also indebted to Sylvia Willems for her organisational support from start to finish. Similarly, I am grateful to Maurice Jenkens for welcoming me at Hexicon's office in Stockholm and to Niklas Hummel and Eduard Dyachuck for their excellent guidance throughout.

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My gratitude extends to my friends and family, whose support was invaluable and which I never can fully acknowledge. I owe a special debt of gratitude towards Tanuj Tanmay, a dear study friend, for showing me part of his home country.

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List of abbreviations

CAPEX	Capital Expenditure
CTV	Crew Transfer Vessel
DM	Decision maker
EC	European Commission
FAO	Food and Agriculture Organisation
FLS	Fatigue Limit State
IMTA	Integrated Multitrophic Aquaculture
OPEX	Operating Expenditure
MCDA	Multiple Criteria Decision Analysis
MUP	Multi-use platform
O&M	Operation and Maintenance
SOV	Service Operation Vessel
TLP	Tension leg platform
ULS	Ultimate Limit State

Chapter 1

Introduction

1.1 Motivation

In the near future, our oceans will be subjected to wide-spread development of offshore infrastructures: offshore wind energy is already experiencing a sharp increase and the aquaculture industry is on the verge of expanding its operations offshore. Not only does installation and operation of these facilities exert environmental pressure on the marine environment, it also requires a lot of space. Besides, offshore operation induces high costs and brings new technical challenges for both the wind energy and aquaculture industry. Hence, it is likely that combining energy and food production in multi-use platforms (MUPs) can offer synergies that result in both economic and environmental benefits [68].

A key initiative that led to this thesis work is “The Ocean of Tomorrow", a program initiated by the European Commission (EC) to study marine and maritime challenges, aiming to foster multi-disciplinary approaches and cross-fertilization between economic sectors and various scientific disciplines. Interest in the subject from an academic perspective is demonstrated by Van Kuik et al. in a report for the European Academy for Wind Energy, which identifies the scientific challenge “To establish possibilities for sustainable protein harvest and food production at sea” as part of the long-term research challenges in wind energy [66].

Another incentive for this study has been the interest in industry for multi-use platforms, which on one side is expressed by the aquaculture industry in stakeholder dialogues in Germany [68] and on the other by large companies such as Equinor (formerly Statoil) and Ørsted (formerly Dong Energy) through their cooperation in the EC-funded MERMAID research program. Industrial interest is also demonstrated by the recent launch of an accelerator program initiated by leading international organisations Equinor, McKinsey & Company, Kongsberg and Techstars which aims to guide entrepreneurs to build the energy platforms of the future.

They have good reason to do so. Both offshore floating wind energy and offshore aquaculture are in an early stage of development, which leaves room for early consideration of integrated solutions. While individual researchers and joint research programs have studied environmental, socio-economic and policy related aspects of MUPs, the technical challenges and potential economic benefits have so far not been studied in detail [8].

Therefore, the central aim of this research is to study the underlying technical challenges and economics that may form either a barrier or incentive for the development of the multi-use concept. Ultimately, the results of this study may help to guide efforts towards smarter use of ocean space.

1.2 Previous studies on the benefits of multi-use farms

This section shortly outlines previous studies on the benefits of multi-use farms, implicitly articulating the need for a technical approach, and presents existing concepts. Most information on multi-use of ocean space is available in the form of grey literature such as presentation slides and short reports. Especially the number of peer-reviewed articles on the subject is scarce.

However, the MUP idea has been studied by researchers across several disciplines. Bela Buck has written an extensive review of current developments of multi-use platforms from an aquaculture perspective and has been advocating multi-use of offshore platforms in Germany for the past 15 years [9]. His work focuses primarily on mussels and seaweed in near-shore wind farms. In addition, the socio-economics of multi-use platforms have recently been studied by Phoebe Koundouri [37]. Moreover, Mee has indicated complementary benefits and policy issues of integrated wind energy and aquaculture farms and questioned wind farm owners in the UK on their willingness to accept aquaculture within their project [47].

The potential economic benefits that result from cooperative use of offshore locations are listed by many. One of the main economic advantages would be shared installation costs and operation and maintenance (O&M) costs between aquaculture and offshore wind farms [48][25]. However, the estimations of the economic potential are rather superficial and mostly based on a simple business case, which stresses the need for further study.

Lastly, this section concludes with the presentation of four multi-use concepts retrieved from literature, presented in figure 1.1 to give a first impression of what a multi-use platform may look like in the future. The first three concepts were part of the EC-funded Ocean of Tomorrow program. A short description is given below.

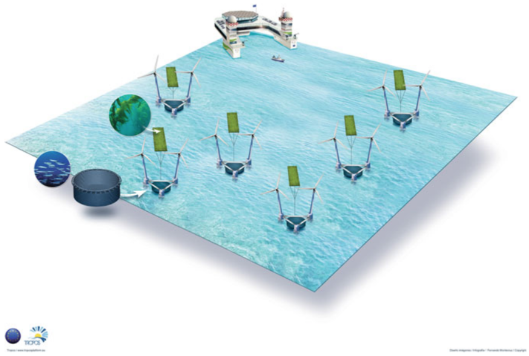
1. The MERMAID project (top-left) was primarily focused on combining energy and food production and reducing ocean space, and features distributed fish cages between offshore wind turbines.

2. The TROPOS project (top-right) focused on a modular platform, hosting a wide variety of activities. Its main objective is to facilitate leisure, oceanic observation and to serve as a host for maritime transport. Besides, next to a large central module, it features separate cage culture and algae production units, powered by wind energy.

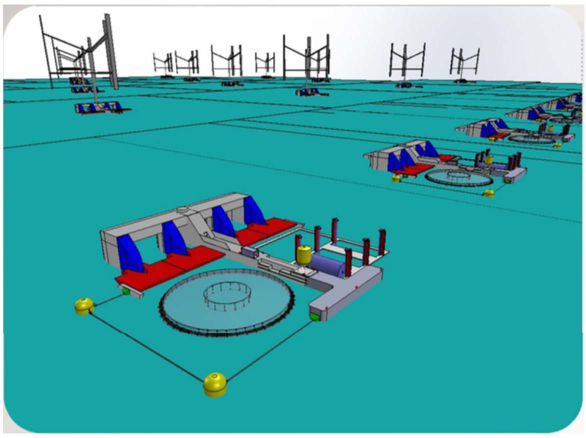
3. The H2OCEAN project (bottom-left) aimed primarily to integrate offshore wind energy and wave energy. The platform design also features multi-trophic aquaculture production consisting of a fish cage and algae units.

4. A separate study by Wei He (bottom-right) delivered a conceptual design of a dual-use jacket structure, utilized for wind energy and salmon cage culture [24].

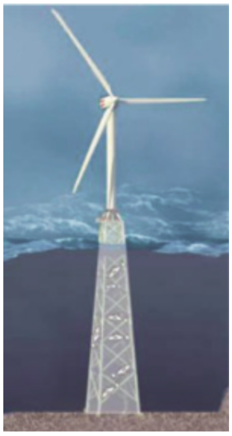
(a) MERMAID conceptual design [25]



(b) TROPOS conceptual modular design [9]



(c) H2OCEAN conceptual design [5]



(d) Dual-use jacket structure [24]

Fig. 1.1 Overview of various multi-use platform designs from previous research projects

1.3 Scope

The focus of this research is on the integration of Atlantic Salmon production in offshore floating wind farms.

One the one hand, the collaboration with Hexicon AB, a Swedish engineering house developing floating wind power, led to the focus on floating wind energy structures and exclusion of bottom-founded alternatives.

On the other hand, the choice for Atlantic Salmon was governed by a couple of reasons. First, because the industry is keen on moving offshore [6, 54]. Second, because wind energy competence could be leveraged to develop offshore fish farming in a multi-use environment, as pointed out by Fredheim [19]. Third, because Atlantic Salmon is one of the most mature industries in marine aquaculture, reaching a production of 2,5 million tonnes each year, most of which is farmed [45]. Fourth, because the industry has high-growth ambitions. Norway, a major producer of salmon has set targets for tripling the salmon production by 2030 and hopes to quadruple it by 2050 [16]. Fifth, because technological innovative solutions are required. According to Thor Hukkelas who leads R&D at Kongsberg Maritime, “scaling up of traditional aquaculture is not going to reach these high-growth ambitions" [16]. This leaves an interesting engineering challenge. Lastly, because culture methods for other types of finfish are largely based on Atlantic salmon farming methods, it is thought that the outcomes of this report can be relevant to other species as well.

It is worth noting that there has been an increased interest in combining the culture of fed species (e.g. fin fish) with inorganic extractive aquaculture species (e.g. seaweeds), which is described as Integrated Multitrophic Aquaculture (IMTA) [64]. The culture of seaweed and mussels in wind farms was studied by various researchers and will not be investigated in this study, but opportunities for IMTA in floating wind farms with integrated salmon culture could be investigated in a follow-up of this research.

1.4 Objectives

The aim expressed in section 1.1, contribution to the existing body of research outlined in section 1.2 and scope outlined in section 1.3 can be summarized into the following objective:

To make recommendations regarding the further development of smart use of ocean space, by providing a clear insight into technical challenges and cost-reduction opportunities of integrating salmon production in floating offshore wind farms.

The following three sub-objectives guide the high-level steps which are taken to achieve the main objective. Chapter 3 is dedicated to explain the research approach and structure in more detail.

1. *To create an overview of MUP concepts, by mapping out existing concepts and by generating new concepts.*
2. *To set-up a decision-making framework to evaluate, compare and rank the concepts while systematically generating insights during the various stages of the process.*
3. *To provide insight into technical challenges and cost-reduction opportunities, by evaluating one preferred concept in more detail.*

Chapter 4 and 5 treat respectively the methodology and execution of the first two objectives. Chapter 6 and 7 address the third objective.

1.5 Thesis outline

The organisation of this thesis is as follows:

- *Chapter 2 -Background* provides a short introduction to floating wind energy and salmon production for the reader who is unfamiliar with one or both of these topics.
- *Chapter 3 - Research Methodologies* outlines the research methodology that was used throughout this study.
- *Chapter 4 - Conceptual Design — Methodology* proposes a framework for the conceptual design and evaluation of multi-use concepts.
- *Chapter 5 - Conceptual Design — Results* presents a range of concepts, illustrating what multi-use platform may look like in the future, and selects a preferred concept using the methodology defined in Chapter 4.
- *Chapter 6 - Preliminary Design Evaluation* is dedicated to a more detailed analysis of the engineering challenges and cost-reduction potential of multi-use platforms, based on the preferred concept chosen in Chapter 5. The result is a list of threats and opportunities, which may guide future research efforts.
- *Chapter 7 - Key focus areas* distils four key items of the list produced in Chapter 6 and analyses them in more detail. Subsequently, the list is updated based on the newly obtained insights.
- *Chapter 8 - Conclusions* presents the conclusions and outlines recommendations for the further development of multi-use platforms.

Chapter 2

Background

This chapter is dedicated to briefly introduce the reader to offshore floating wind energy and Atlantic Salmon farming by outlining practices and general trends within the two industries.

2.1 Floating wind energy

In wind energy, the gradual shift from coastal to offshore locations leads to sites with greater water depths and at larger distances from shore (see figure 2.1) [46][65]. Whereas the support structures used today can support wind turbines up to water depths of approximately 60m, floating foundations enable wind energy production in water depths far beyond.

Although the development of floating technology for wind energy is still in an early stage, the world-wide wind energy resource in deep waters is considerable [31] (see also table 2.1).

Table 2.1 Potential for floating wind energy (data from [69])

Country / region	Share of offshore wind resource in +60m depth	Potential capacity
Europe	80%	4000 GW
USA	60%	2450 GW
Japan	80%	90 GW

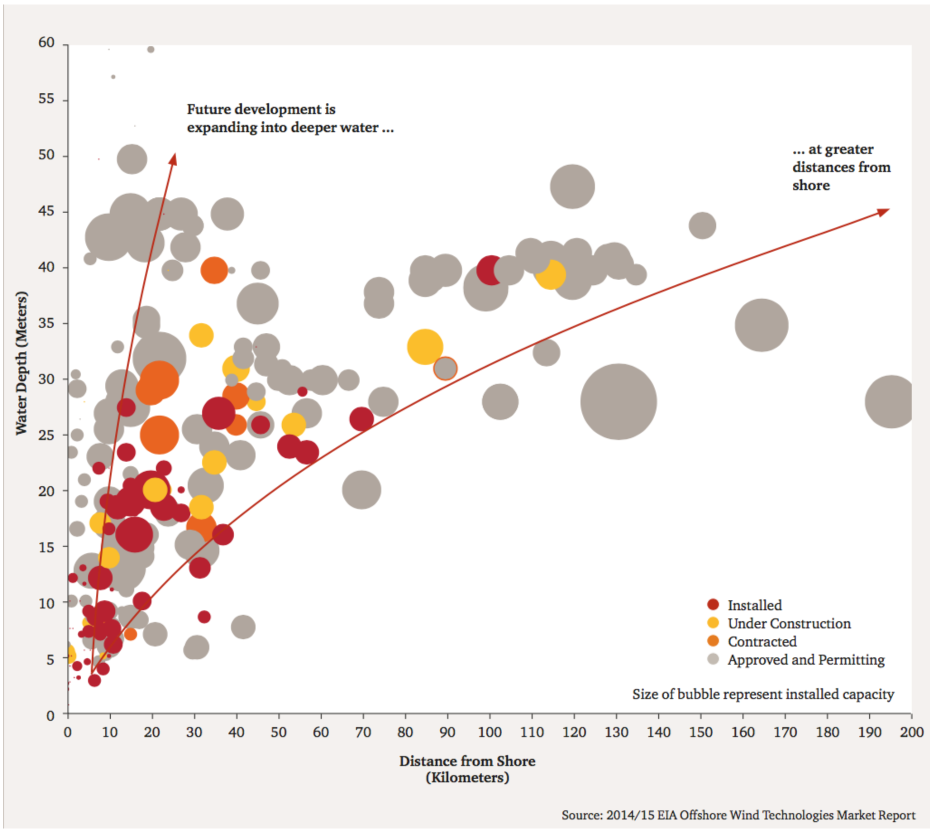
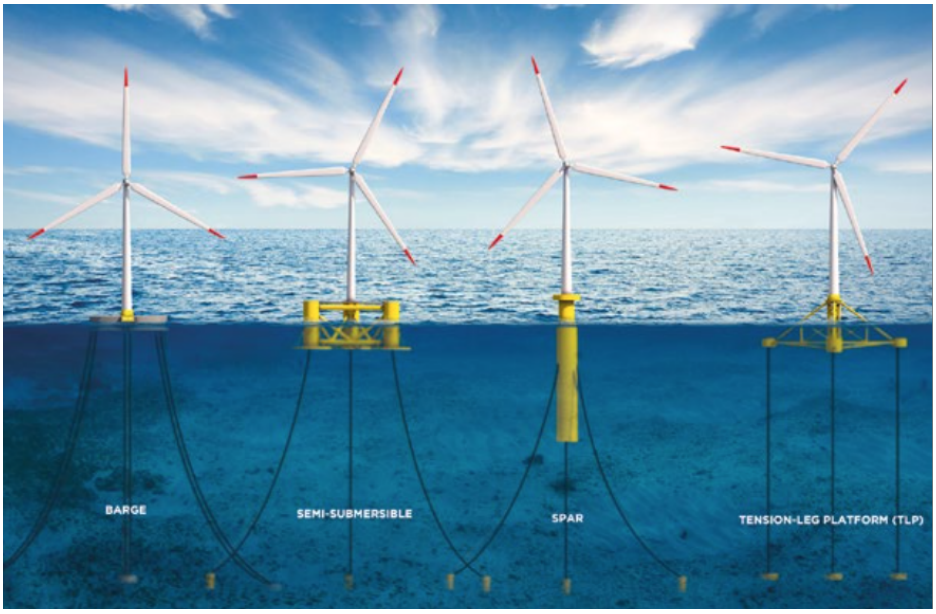


Fig. 2.1 Trend to deeper waters and offshore locations [65]

The concept of floating offshore structures is not new, and was pioneered by the oil and gas industry. For wind energy, the technical feasibility of floating foundations has recently been proven by Hywind, a 30 MW farm operated by Equinor (formerly Statoil) and Masdar. Commissioned in October 2017, it is the first commercial floating wind farm. Commercialisation of other farms is anticipated between 2020 and 2025 [30].

At present, there are more than 30 concepts under development of which two-thirds originate from Europe. They can be categorised in four main types: the barge, spar-buoy, semi-submersible and the tension leg platform (TLP), illustrated in figure 2.2a. Within these categories different types exist, such as the semi-submersible platform currently in development by Hexicon, which consists of two turbines on one platform (figure 2.2b).

For a detailed review of offshore floating wind energy technologies the reader is referred to James R. et al. [31].



(a) Classificiation of four dominant floating support structures. From left to right: Barge, Semi-submersible, Spar-buoy, Tension Leg Platform [69].

(b) Illustration of the semi-submersible Dounreay Trì multi-turbine platform developed by Hexicon. (Courtesy: Hexicon)

Fig. 2.2 Presentation of various support structure concepts for floating wind energy

2.2 Atlantic salmon production

Before zooming in on Atlantic Salmon production, a concise industry-level perspective on aquaculture is given.

2.2.1 Aquaculture

Aquaculture is the aquatic equivalent of agriculture on land. Driven by parameters such as population increase, food security, employment, stresses on fresh water resources and uncertainty associated with wild fish stocks, the demand for cultured protein from the sea is growing and the share of aquaculture compared to wild capture is steadily increasing [58], illustrated by the Food and Agriculture Organisation (FAO) in figure 2.3.

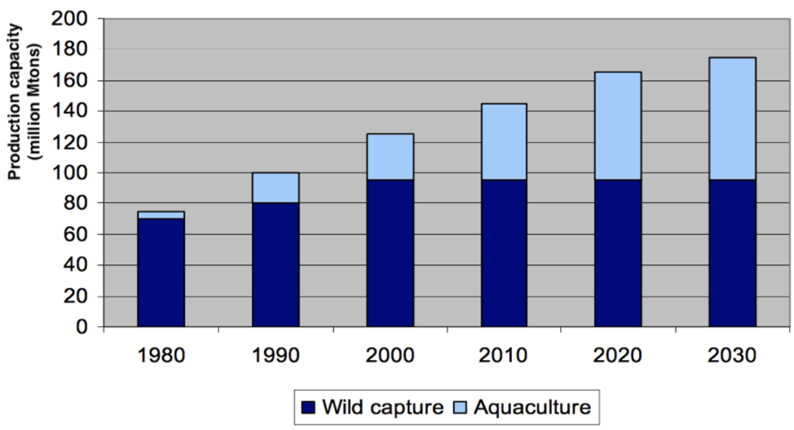
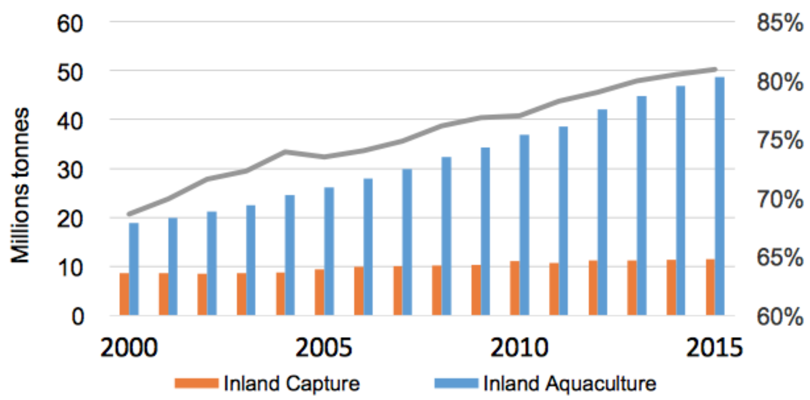


Fig. 2.3 Projections for aquaculture production capacity for 2030 [19].

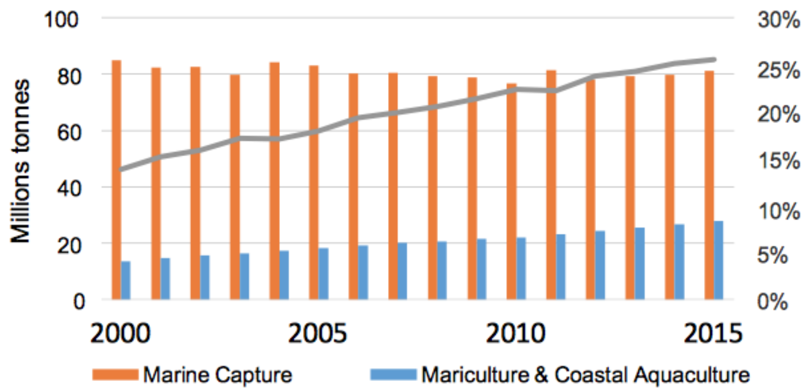
Unlike popular belief, not all aquaculture is located in a sea-environment. On the contrary, most aquaculture is conducted inland. It is useful to segment aquaculture into its component parts in order to identify the main drivers of the observed and forecast industry growth. For this purpose, the FAO Fisheries and Aquaculture Department distinguishes between production in marine and inland water (see also figures 2.4a and 2.4b). [1]

First, the figures demonstrate that inland aquaculture is the main driver of the total aquaculture growth, both in size and growth rate. It claims a 29% share in total production and yearly production has grown with 30 million tonnes between 2000-2015. Mariculture's yearly production, which accounts for 16% in 2015, grew almost 15 million tonnes in the

[1]Marine aquaculture, mariculture, is the segment of aquaculture that cultivates marine organisms in a salt-water or brackish environment; either in the open ocean, an enclosed portion of the ocean, or tanks or ponds filled with seawater. In contrast, inland aquaculture occurs in fresh water resources.



(a) Distribution between inland aquaculture and inland capture [72]



(b) Distribution between mariculture and marine capture [72].

Fig. 2.4 Comparison of inland and marine aquaculture production volumes and growth rate. The grey line represents the share of aquaculture in the total inland and marine production segments.

same period[2].

Second, the FAO demonstrates that the share of aquaculture with respect to total production differs among the two types. Whereas aquaculture dominates the inland production at over 80% of the total, production at sea is still heavily dominated by capture and aquaculture only achieves a 26% share. To nuance this view, it should be noted that in absolute terms, marine capture is eight times larger than inland capture and the total marine aquaculture production equals 50% of inland aquaculture production.

[2]Mariculture can be divided into several types: fin fish (e.g. Atlantic Salmon), crustacae (e.g. crabs, shrimp), molluscs (e.g. mussels, oysters) and other aquatic animals (e.g. algae). Their share within marine aquaculture, based on live weight percentage, is 24%, 16%, 58 % and 13% respectively.

Factors hampering marine aquaculture growth are spatial planning issues and ecological impact of farm waste. To circumvent these, marine aquaculture (fin fish culture in particular) is looking to expand operations offshore [33]. It is thought that in exposed environments, due to higher current speeds and availability of space, pollution can be reduced and interaction with local stakeholders minimized. The salmon industry is a leading player in this transition.

2.2.2 Introduction to salmon farming

2.2.2.1 Production method

Sea cage production of Atlantic Salmon originates from the 1960s in Norway, where it was attempted to raise salmon to marketable size (illustrated in figure 2.5a). Since then, it has grown rapidly and is now conducted on much larger scale in sheltered coastal areas (figure 2.5b).

(a) Cage culture in 1960s (source: DNB)

(b) Cage culture today

Fig. 2.5 Salmon farming in 1960 and today

The culture of Atlantic Salmon takes approximately three years and consists of various stages, which are illustrated in figure 2.6. After fertilisation of eggs and controlled fresh-water growth to approximately 100 grams, the fish are transported to seawater cages where they will grow to an optimal harvest weight between 4—5 kg in a period of 14 to 24 months.

Solely the growing stage in seawater is the subject of this study. After this growing stage, the fish are brought back to shore to processing plants, where they are slaughtered, gutted and sold on ice in a box.

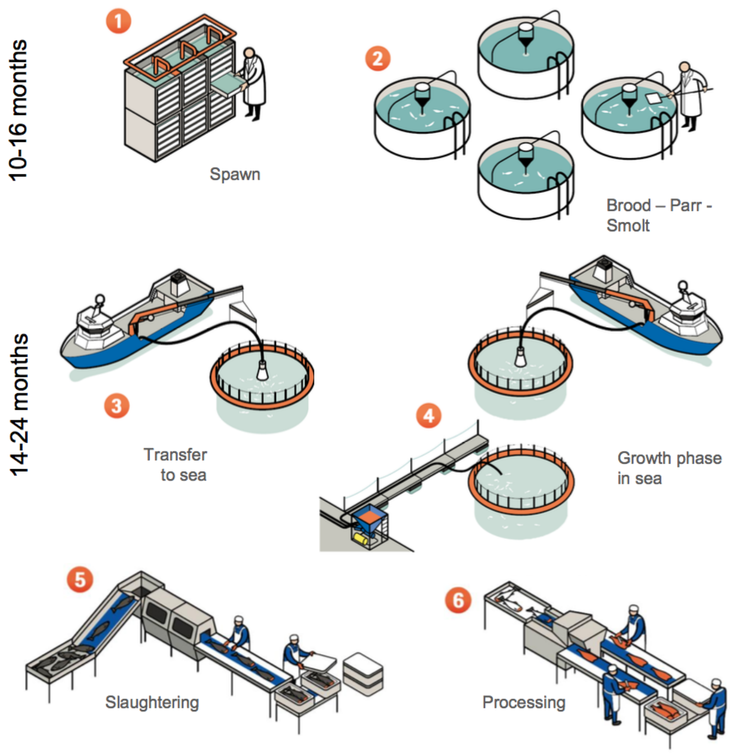


Fig. 2.6 Salmon production cycle [45]

2.2.2.2 Technological developments

Technology development in aquaculture is strongly supported by governments and institutions world-wide. For salmon farming that is especially by Norway, which has spurred the development of new concepts and salmon farming methods.

Norwegian salmon company Salmar has developed a large offshore pilot farm called Ocean Farm 1 to cope with the more exposed environment in offshore locations (see figure 2.7). Like the Hywind floating wind farm discussed in previous section, it was commissioned in 2017. The concept is huge compared to traditional aquaculture net-pens. Whereas traditional net-pens have a volume of approximately 35.000 m^3, Ocean Farm 1 spans 245.000 m^3 and hosts up to 1.5 million juvenile salmon. While this concept has a 110m diameter, the next generation is expected to span 180m.

Salmar is not the only company involved in offshore farming. Other concepts are of various shapes and sizes, including fully submersible cages, mobile ships, and enclosed recirculating

Fig. 2.7 (Pilot) offshore salmon farming station Ocean Farm 1 [54]

systems. A list of licence applications, submitted to the Norwegian Directorate of Fisheries, is added in Appendix A to highlight the diversity and number of developments.

The industry's high-growth ambitions and willingness to move offshore are opposed by little experience with fish farming in exposed areas. Facing similar challenges as offshore (floating) wind energy, it would be interesting to investigate joint solutions in multi-use concepts [19].

Chapter 3

Research Methodologies

This chapter provides a description of the research methodology, divided into the high-level approach in section 3.1 and and overview of the objectives and practical organisation of research activities in section 3.2. It is advised to read this chapter in advance, but it can also be consulted while reading subsequent chapters. The chapter concludes with outlining first steps towards concept validation in section 3.3.

3.1 Research approach

3.1.1 Identifying synergies, opportunities and threats

This study is aimed at identifying possible synergies between offshore floating wind energy and salmon production. Synergies are defined by Cambridge Dictionary as "the combined power of a group of things when they are working together that is greater than the total power achieved by each working separately" [1]. In other words, it is the concept of the whole being greater than the sum of its parts.

When studied separately, both floating wind energy and exposed aquaculture are immature technologies which offer many opportunities and face a similar amount of threats. In this study it is aimed at isolating those opportunities and threats which are exclusively associated to multi-use. By doing so, an idea can be obtained about any synergetic effects which could be realised, which can be seen as the difference between the whole and the sum of its parts.

This idea of isolating those opportunities and threats associated to multi-use materialises in the research design by establishing reference concepts with which the multi-use concept can be compared. The performance of the multi-use concept on a given aspect is then not assessed based on its individual performance, but on how it compares to the two stand-alone concepts. Figure 3.1 aims to schematically illustrate that the relevant opportunities and threats are found by comparison of the multi-use concepts with the stand-alone reference.

The choice of reference concept in a final comparison depends on the multi-use concept which is eventually designed and selected. Ultimately, the 'best' multi-use concept should offer at least the equivalent and preferable more than the sum of the 'best' floating wind energy reference and the 'best' aquaculture reference. [1] However, because the technologies are very immature, it is unknown at this stage which concept will be 'best' for stand-alone floating wind energy or aquaculture.

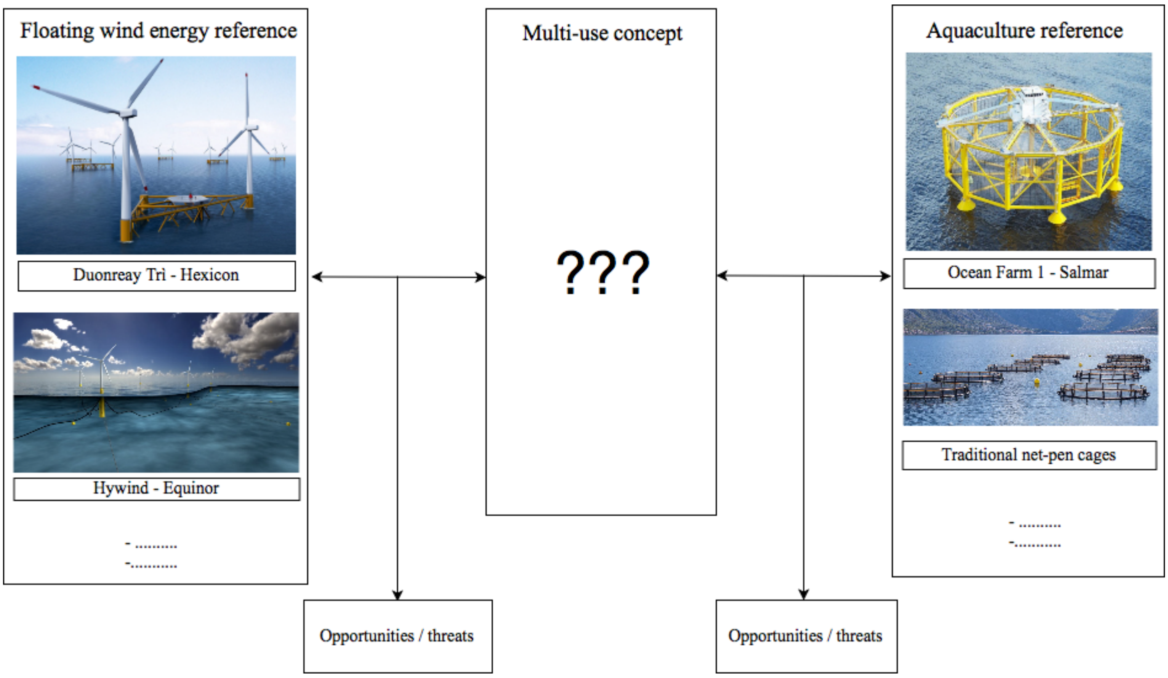


Fig. 3.1 Schematic illustration of isolating the opportunities/threats related exclusively to multi-use by comparing the (unknown) multi-use concept with stand-alone core concepts as a reference

[1] In this context, 'best' can be interpreted as for instance the most cost-effective, environmentally friendly, safest, or a combination of these and a plethora of other criteria.

3.1.2 The role of design in relation to the research objective

In the introduction of his book about aircraft design, Raymer [51, p.1] states:

> “To the uninitiated, design looks a lot like drafting (or in the modern world, computer-aided drafting). The designer’s product is a drawing, and the designer spends the day hunched over a drafting table or computer terminal."

To which he adds:

> "However, the designer’s real work is mostly mental (....) Design is not just the actual layout, but also the analytical processes used to determine what should be designed and how the design should be modified to better meet the requirements."

Endorsing this view on the design process, a minor goal of the design activity is to illustrate what a multi-use platform may look like in the future. Before doing so, the design methodology should be structured such that it enables to present, evaluate, compare and rank a diverse range of new alternatives, which constitutes the majority of the work.

Most importantly, design is seen as means to further the end of creating insights regarding the development of multi-use platforms. While many of the trade-offs which constitute a design challenge lead to intuitive solutions, application of a structured design methodology can help to give insight in these trade-offs and thereby helps to exceed the intuitive level.

3.1.3 Positioning of this study in the design sequence

The design sequence of a concept can be divided into several stages. Following the interpretation of Raymer, displayed in figure 3.2, this study is positioned in the earliest stages of the concept development. [2]

It should be noted that the level of detail which permits assigning the label ‘preliminary design’ may vary and is subject to opinion. Here, the label is used mainly to indicate that the level of detail exceeds that of the conceptual design phase. It includes simple assessments that are typical in preliminary design work, but certainly does not check all boxes of a preliminary design checklist that is standard in industry. To avoid confusion, the preliminary design work will be addressed as Preliminary Design Evaluation in the rest of this report.

[2] It should be noted that, because design is an iterative process, the stages are not strictly followed from top to bottom.

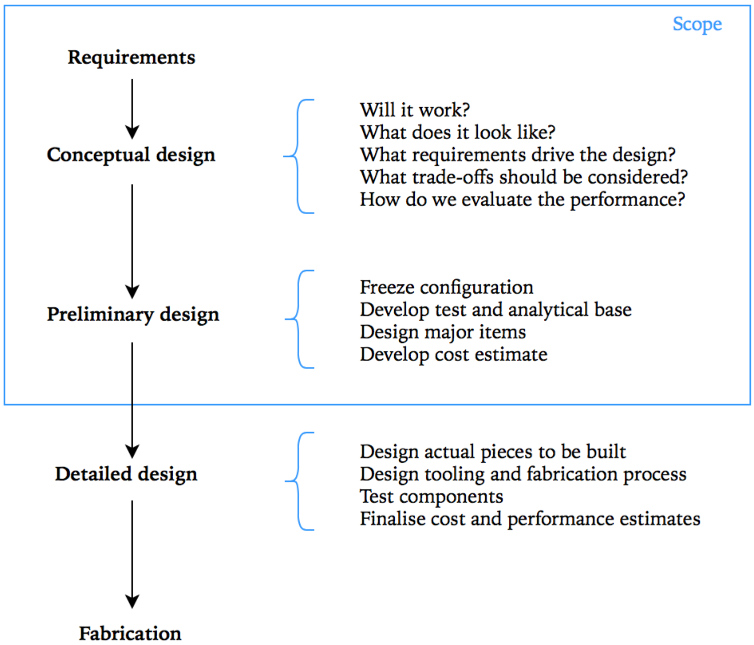


Fig. 3.2 Stages of design and scope of this work (adapted from Raymer et al.[51])

Section 3.2 is dedicated to the organisation of this research within this domain.

3.2 Research structure

3.2.1 General structure of the research

The approach presented in the previous section materialises into the research structure following figure 3.3, which can shortly be described in words as follows.

The first step is to formulate overall objectives and highlight the problem statement, which was done in the introduction of this thesis. What follows is a set of detailed objectives which guide the subsequent steps; they are discussed separately for the conceptual design and preliminary design analysis stage in sections 3.2.2.1 and 3.2.3.1.

The conceptual design phase aims to present, evaluate, compare and rank a range of multi-use concepts and concludes with identification of a set of superior concepts, of which one concept will be chosen and analysed in more detail.

In the preliminary design stage, the most preferred concept is analysed by studying the interactions between the wind energy and aquaculture component and by comparing the performance of multi-use concept against the stand-alone references. A list of threats and opportunities is developed, from which technical items are selected and studied in more detail. The newly obtained knowledge is used to update the list of opportunities and threats, which may guide future efforts for integrating salmon production in offshore wind farms.

The next sections discuss the two main stages Conceptual Design and Preliminary Design Analysis in more detail.

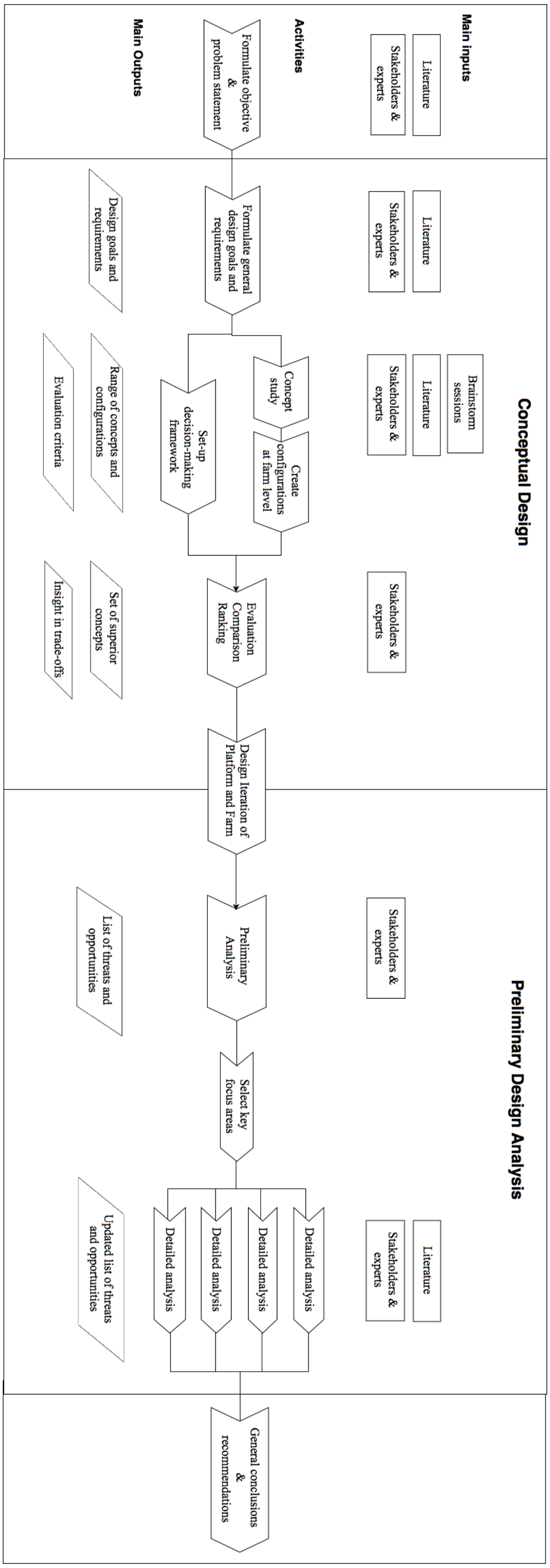


Fig. 3.3 Schematic illustration of the research structure

3.2.2 Description of the Conceptual Design stage

3.2.2.1 Objectives guiding the Conceptual Design

In this study, the challenge the designer is confronted with is to come up with an innovative concept which satisfies the needs of various stakeholders, possessing only a limited amount of information. Starting from a blank sheet of paper, questions arise such as: what will it look like? How to evaluate its performance? What are the trade-offs that need to be considered?

To give direction to these questions, the following objectives are set:

- To formulate general design goals and requirements, by studying relevant literature and consulting experts

- To present a range of innovative concepts, by studying existing concepts and generating new concepts.

- To select a set of superior alternatives, eventually leading to the selection of one 'best' concept, by creating a decision-making framework which stimulates and facilitates to:
  - identify a set of evaluation criteria
  - expose relevant trade-offs
  - identify stakeholder preference, and study the impact of different preferences on the decision
  - study the impact of new information when it becomes available, without requiring major modifications
  - provide measurable arguments to support the decision.
  - retrace the rationale for a decision to explicitly stated assumptions rather than intuition

3.2.2.2 Structure of the Conceptual Design stage

The conceptual design stage consists of a series of activities, outlined in figure 3.3.This section gives a high-level description of the main steps. The detailed methodology is highlighted in chapter 4 and the execution is presented in chapter 5. It should be noted that although the flowchart suggest that the process is strictly followed from left to right, the iterative nature of design induces continuous interaction between the various stages.

The conceptual design stage starts with identification of goals and requirements through literature study and consultation of relevant experts. A list of criteria is drafted which both helps with drafting a design in an early stage and evaluation of the alternatives in a later stage.

The ‘concept study’ block can on the one hand be seen as blank-sheet-of-paper design work, where the designer tries to create a range of novel concepts during brainstorm sessions. On the other hand, existing concepts are studied. A final selection is then made and scaled to farm level by forming configurations.

Simultaneously, a decision-making framework is designed to help evaluate, compare and rank the alternative configurations, which are evaluated in confrontation with the aforementioned list of criteria. With the implementation of the decision-making framework it is aimed at detecting showstoppers at an early stage and reducing the chance of ending up with a poor-performing concept in later stages. By making explicit trade-offs and offering easy to analyse outputs, the framework should help to exceed the intuitive level. This would allow engineers, farm-operators, policy-makers, and other stakeholders to discuss the future of multi-use platforms in a structured and transparent manner. Directly tied to this, the framework allows for integration of new information such as new concepts, evaluation criteria, or stakeholder preference with relative ease.

A most preferred configuration is selected and analysed in more detail in the preliminary design stage, which is discussed in the next section.

3.2.3 Description of the Preliminary Design Analysis stage

3.2.3.1 Objectives guiding the Preliminary Design Analysis

In contrast to the conceptual design stage, the preliminary design analysis stage is of a ‘converging’ nature. The aim of this stage is to identify and list threats and opportunities regarding engineering challenges and cost-reductions, based on analysis of the most preferred configuration selected in the conceptual design stage. From this list, a selection will be treated in more detail to provide deeper insights in what are considered the most pressing or promising areas.

The following objectives guide the Preliminary Design Analysis stage:

1. To identify engineering challenges associated to the multi-use platform
2. To identify, and quantify where possible, the opportunities for cost reduction
3. To identify ways in which one module can support or instead may hamper the functioning of the other module, by studying the interactions between the two modules.

3.2.3.2 Structure of the Preliminary Design Analysis

It is intended to achieve these objectives by following the steps outlined in figure 3.3. Analogous to the previous section, this section explains the high-level rationale which led to the establishment of this structure. The more detailed methodology and execution related to the general analysis are presented in chapter 6. Chapter 7 addresses the four focus areas.

Before starting the preliminary analysis, the design of the preferred concept is reviewed and updated in section 6.1 in light of newly obtained information. The review leads to a new configuration and sizing of the farm, determined in section 6.1.4. A short reflection on the configuration selection is presented in section 6.2.

When the preferred concept is updated and the decision to opt for this concept remains unchanged, the concept is analysed in section 6.3 along a list of evaluation items. This activity is meant to identify opportunities and threats, which will be gathered in a list format.

Subsequently, a selection of opportunities and threats is made and studied in more detail in chapter 7. This step aims to progress, where possible, the level of knowledge from identification to quantification. The newly obtained insights are then used to re-assess and update the list of opportunities and threats, which may ultimately guide future efforts for integrating salmon production in offshore wind farms.

3.3 First steps towards concept validation

Especially in design-oriented research, it is crucial to reflect on results and assumptions in an early stage instead of merely at the end, because the decisions made in the beginning greatly impact the outcome. This report borrows ideas and terminology related to concept validation from the European Operational Concept Validation Methodology (E-OCVM) framework, which was originally created "to provide structure and transparancy to air traffic management operational concepts as they progress from early phases of development towards implementation." [17].

A prerequisite for successful concept development is to ensure that stakeholder's operational requirements are aligned with proposed solutions (the concepts presented in this study). The E-OCVM framework prescribes several activities to support this, of which three were directly applied in this project.

- Engage a large group of experts from various fields
- Identify and evaluate a wide range of alternatives
- Adequately document exercises and associated assumptions

While the latter two suggestions are rather straightforward, the implementation of the first will be explained in more detail. Where possible, it has been attempted to reflect on the results and assumptions through semi-structured interviews with experts in both the wind energy and aquaculture sector. This helped to identify and correct inconsistencies in numbers and assumptions from the first stage, as well as to ensure that the results were aligned with stakeholder needs. In appendix C, the group of experts which has contributed to this project is listed.

From nearly all relevant fields of expertise, at least one expert was involved in this project. Unfortunately, expertise from the salmon farming companies was not reached, which leads to more uncertainty regarding the validity of the final design and the results that follow from that. To partially compensate for this, literature study was conducted which resulted for instance in the discovery of a publicly available survey conducted with 20 representatives from different parts of the aquaculture industry (included in Appendix E). This helped to check the most important assumptions regarding stakeholder needs and provided valuable information about the requirements of offshore cages during the design.

A last comment is related to the set-up of the research structure. It is likely that, when asked to comment on this work, (aquaculture) experts will suggest adjustments to the design or to the goals and requirements that govern the design, which may have serious consequences for concept exploration and selection. Anticipating such events was one of the reasons for choosing a rigorous decision-making framework in the conceptual design stage (presented in chapter 4.4) instead of an intuitive approach. When, during or after the project, more information would become available, the framework lends itself to incorporate feedback, new concepts and additional criteria with relative ease.

Chapter 4

Conceptual Design - Methodology

This chapter presents the methodology used throughout the conceptual design stage, starting with the approach for establishing design goals and requirements in section 4.1. Subsequently, the concept study is addressed in section 4.2 followed by creating configurations at farm level in section 4.3. Lastly, section 4.4 outlines the decision-making framework which consists of the stages evaluation, comparison and ranking.

4.1 Establishing design goals and requirements

The first step in a design process is to identify the goals and, derived from that, the requirements the design has to fulfil. Assigning correct requirements and identifying effective design parameters is crucial for the final outcome [58]. In the first place, insight in goals and requirements was obtained by consulting scientific literature and various other information sources such as presentations and annual reports of relevant companies. Where possible, it has been attempted to elicit and analyse the requirements and assumptions together with experts in relevant fields. Their views were documented and are integrated in this report.

The study of 'multi-use' by definition involves two or more subjects. It is useful to study the similarities and differences in their requirements to gain an understanding of the overlap between the two industries. This is done by zooming in through the lens of both aquaculture and wind energy, illustrated in figure 4.1. This technique can be applied to any specific area of study, for instance logistics or costs. For each area of study, there may be a large, small or no overlap. Studying that overlap for the different components which make up the wind energy and aquaculture activity helps to expose mutual as well as conflicting goals and requirements.

To do this in a structured manner, the functions and requirements were segmented into their component parts and organised in a hierarchic tree-shaped diagram. Not only does this exercise help prioritize in early design iterations, it also helps to create more diverse and innovative concepts which is described in the next section.

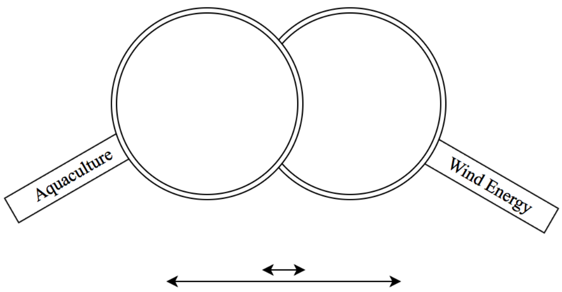


Fig. 4.1 Illustration of studying the interface between wind energy and aquaculture by zooming in on the similarities and differences

4.2 Concept study

This section shortly states how the concept study is organized, which is divided into generation of new concept as well as analysis and modification of existing concepts.

During the concept generation phase, which should be a creative process leading to innovative solutions, it was considered important to prevent thinking of economic and technological factors as strict requirements or constraints. Therefore, innovative solutions that may not be economically viable or technologically feasible today were also considered, as they might become so in the future. In line with the conceptual framework proposed by Shainee et al., costs and technology readiness are considered as an "evaluation criterion in the process of choosing among a set of viable options after the conceptualization stage"[58].

To generate new concepts several brainstorming sessions were held, both individually and in small groups of 3—8 participants. First of all, a structured session was held with students, some in wind energy and most from other disciplines, aiming to come up with new concepts without being biased by existing practices or concepts. The purpose of the brainstorm was first to come up with a design that could fulfil all goals simultaneously. Subsequently, every person was given a particular goal, picked from the tree-shaped hierarchy of goals and requirements introduced in the previous section, for which he/she had to brainstorm for concepts which would maximize the utility for that goal. Temporarily neglecting other goals and requirements leads to a greater diversity of concepts.

Then, after looking at creative new options, a range of existing wind energy and aquaculture concepts was evaluated and modified to MUP platforms, leading to a seemingly more realistic and familiar range of concepts.

After the first session, several unstructured and semi-structured sessions were held with students, professionals and industry experts during interviews or casual meetings.

Following this approach resulted in a wide range of concepts. This range was complemented by existing concepts found in literature. It would be an arduous task to evaluate every single one of them thoroughly, therefore a first sifting was done based mainly on intuitive ideas of the author about the ability of the concept to meet the most basic requirements. It was aimed to arrive at a final selection of 8—10 concepts, allowing more detailed analysis during the time available.

4.3 Creating configurations at farm level

4.3.1 Reasons for scaling to farm level

To allow fair comparison of the candidate concepts, it is important that they are evaluated in light of their performance at farm-level, i.e. in their final configuration. That is for a number of reasons.

First there are scaling issues, because the ratio between installed energy capacity and cage volume is not equal for every platform (see figure 4.2). This leads to an unequal amount of structures when scaling up to a particular farm size. The integration of concepts in a farm is a simple step which calculates how many platforms are required to obtain a given amount of installed capacity for wind energy and aquaculture.

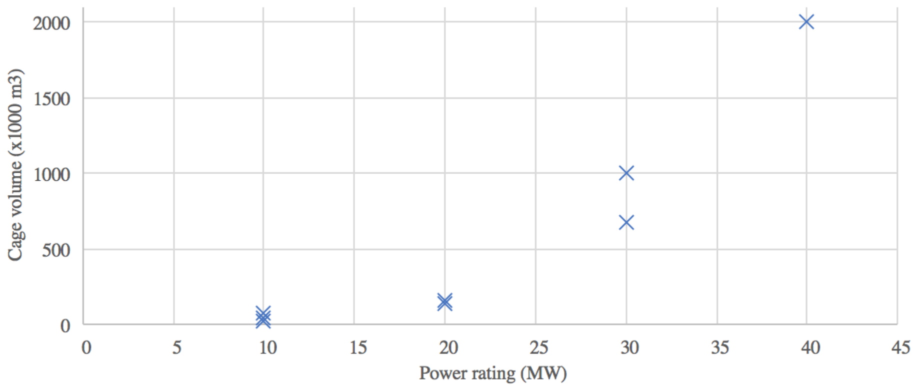


Fig. 4.2 Ratio between installed power capacity and cage volume per concept. The data points come from the concepts presented in chapter 5 and given in table 5.2

Related to that, the meaning of several evaluation criteria reaches beyond platform level. For instance, when comparing costs at platform level, one isolated concept may be cheaper than another. However, to realise a farm, one could need many "cheap" concepts which altogether costs more than few expensive structures. Failing to see the bigger picture risks the decision maker (DM) to end up in a "penny wise, pound foolish" scenario.

In addition, there is the need to aggregate costs at farm level to account for overhead costs, which cannot be directly attributed to a single platform.

After creating a level playing field, the DM can proceed with selection of the best performing configuration.

4.3.2 Dimensioning of the farm

This section specifies the size of the farm, summarized in table 4.1. A relatively large wind farm is chosen because it is expected that farms will have increasingly higher capacity in the future. Similarly, a rated power of 10 MW per turbine is estimated to represent a future offshore wind turbine capacity in 5—10 years from now.

The size of an aquaculture farm is generally expressed in metric tonnes (t) production capacity per year. Because moving offshore will inevitably incur extra costs to the industry, opting for a large-scale facility is the only way to make it economically feasible, according to Richard Langan from New Hampshire University [40]. Inspection of licence applications to the Department of Fisheries in Norway (see also Appendix A) proves that 10.000 tonnes is at the larger end of the spectrum. This view is reinforced by a report issued by the Ireland Marine Institute about offshore farming, in which both a 5.000 and 10.000 tonnes case-study were considered representative [53].

A question which remains unanswered is how to translate Mtons production per year to dimensions, ideally the cage volume. Yearly harvest is dictated by the number of fish and fish growth rate, a complex process which depends on many factors. A case-study by Liu et al. estimates that 3300 Mtons is obtained from a 587,000 m^3 cage [43]. Assuming that the yearly production scales linearly with volume and rearing density is constant, extrapolation leads to a required cage volume of 1.778.000 m^3.

Table 4.1 Case-study parameters: size of the farm

	Value	Units
Wind farm		
Installed capacity	800	MW
Turbine rated power	10	MW
Salmon farm		
Yearly production capacity	10.000	Mtons
Cage volume	1.778.000	m^3

4.4 Evaluation, comparison and ranking

At first, selecting the ‘best’ configuration may seem a straightforward task. However, there exists no normative model of how decision makers should make complex choices, based on multiple criteria, that is without critics. Nevertheless, several methods exist to structure and make explicit the trade-offs the DM should make in order to solve the decision problem.

In a paper discussing how to select MDAO workflows, Sanchez and Zaayer make a useful distinction between *Evaluation*, *Comparison* and *Ranking* [55], which offers an intuitive structure and effectively stages the decision-making process. Figure 4.3 gives an overview of the DM framework which is used in this study and further detailed below.
According to Sanchez, the evaluation stage can be seen as setting the terms and conditions for the decision-making problem. Then, when the rules are established, "solving" the DM-problem can be interpreted in different ways. In this study, solving is interpreted primarily as finding the ‘best’ or ‘most preferred’ alternative, but also aims to identify sets of well-performing alternatives. The two objectives are paired with two methods, demonstrated as separate branches in figure 4.3 .

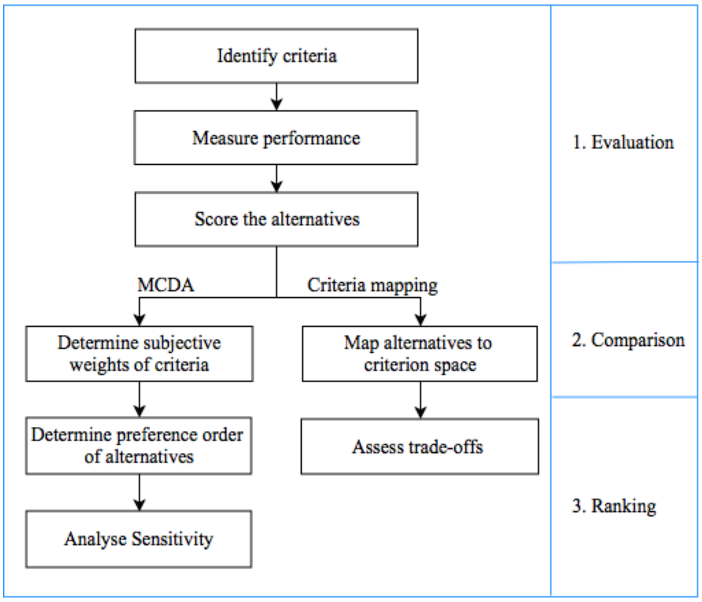


Fig. 4.3 Overview of the decision-making framework

On the one hand, Multi Criteria Decision Analysis (MCDA) was conducted to choose the most preferred alternative within a limited set of options. The decision-making framework proposed in this study follows to a large extent the guideline of Keeney and Raiffa[1] [35] and was complemented by adopting several components of the guideline proposed by Wang for sustainable energy decision-making [67]. It should be noted that while Keeney and Raiffa formally built uncertainty into their model, this study addresses uncertainty at the end of the process through sensitivity analysis, which will be discussed later in this section.

On the other hand, to identify sets of well-performing alternatives and study relevant trade-offs, insights were gained by mapping alternatives' scores to the criterion space. Unlike MCDA, this method allows *a posteriori* articulation of preferences and therefore complements the MCDA procedure.

The following describes these activities in more detail, organised in the three stages: evaluation, comparison and ranking.

4.4.1 Evaluation

The evaluation of configurations is the first and most crucial step in the selection of the 'best' configuration. The output of this activity is a list of criteria and metrics, essentially dictating what constitutes the 'best' design.

4.4.1.1 Identifying criteria

The definition of the criteria follows from the design goals and requirements. Whereas the design goals and requirements are stated on a more general level, the evaluation criteria are more elaborate in order to distinguish between alternatives. To do that effectively and accurately, they need to comply to several 'attributes' or 'principles'. Keeney and Raiffa defined five attributes: completeness, operability, decomposability, non-redundancy and size [35]. The meaning of these attributes will be discussed below.[2]

Completeness addresses the "adequacy of the list of criteria to meet the overall objective and if its sub-objectives cover all areas of concern related to the performance"[55]. Ultimately, the utility of each alternative must be fully captured by the criteria to allow fair

[1]This work was published in 1976 and is still considered a leading framework today[14].

[2]Similarly, Wang defined five principles: the Systemic, Consistency, Independency, Mensurability and Comparability principle [67]. For consistency, this work follows Keeney's definition.

comparison. An issue tree method was applied to segment the criteria, which helps to identify gaps. Inductive and deductive reasoning techniques can be used prove that no gaps exist between the chosen criteria (and objectives) [55].

The *non-redundancy* attribute prescribes that criteria are independent to avoid double counting any effect. When two criteria are correlated, they should in most cases either be combined or one of them discarded. There are cases when two criteria show a correlation, but where it can be argued that none should be discarded. A case like this should be studied with care and evaluated in light of the specific circumstances.

Operability refers to the condition that criteria must be understandable, measurable and useful for making decisions. This criterion ensures that the decision making process is pragmatic and meaningful. The operability attribute prescribes that all criteria should expose differences between alternatives. If all alternatives score the same positive or negative score on a criterion, the operability requirement is not met and the criterion should then be discarded.

Decomposability of the list of criteria prescribes that the criteria can be organised in the form of an issue tree. This allows the segmentation of the decisionmaker's problem into multiple smaller problems, and helps to ensure pairwise independence, which is important for the non-redundancy and completeness attribute.

Size is the last attribute and originates from the thought that there is “great value in avoiding unnecessary complexity" [55]. Hence, the number of criteria should be kept as small as possible.

4.4.1.2 Measuring performance

After the rules for evaluation are set, the alternatives can be evaluated on their performance, which is ideally done quantitatively. If data is unavailable, performance may be expressed qualitatively and binned in categories, for instance ranging from ‘very low’ to ‘very high’.

Subsequently, the set of performance values can be grouped in a performance matrix:

$$P = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}$$

Where x_{ij} is the performance of the i-th alternative on the j-th criterion, n is the number of criteria and m is the number of alternatives [67].

The performance matrix reveals limited information about alternatives’ relative merits, but it has two main advantages.

First, it provides a useful overview to evaluate whether trade-offs between criteria are acceptable. This is an important aspect in MCDA and is called ‘compensation’. It entails the extent to which an alternatives’ poor performance on one criterion can be compensated by good performance on another [22][13]. According to Guitouni, this can be either fully the case (*compensatory*), not the case (*non-compensatory*) or partially the case (*partially compensatory*).

This ‘intuitive’ assessment is not easy and it is not clear at which level it should be applied. Based on inspection of the criteria and scores, an overview of which will be presented in section 5.4.1.3, it was assessed that the decision problem can be assumed fully compensatory; a poor performance on one criterion can be counter-balanced by a good performance on another.

The second advantage of constructing a performance matrix is that it can serve as an aide-mémoire for the decision maker [63]. This attribute can be assigned to the performance matrix because it is an unmodified evaluation of the performance which has not been adjusted by subjective scoring procedures.

4.4.1.3 Scoring the performance

This step should be understood as eliciting the DM's preference to a change in the performance, and can be interpreted as "estimating the parameters in a mathematical function which allow the estimation of a single number index, U, to express the decision maker's overall valuation of an option in terms of the value of its performance on each of the separate criteria." [14]

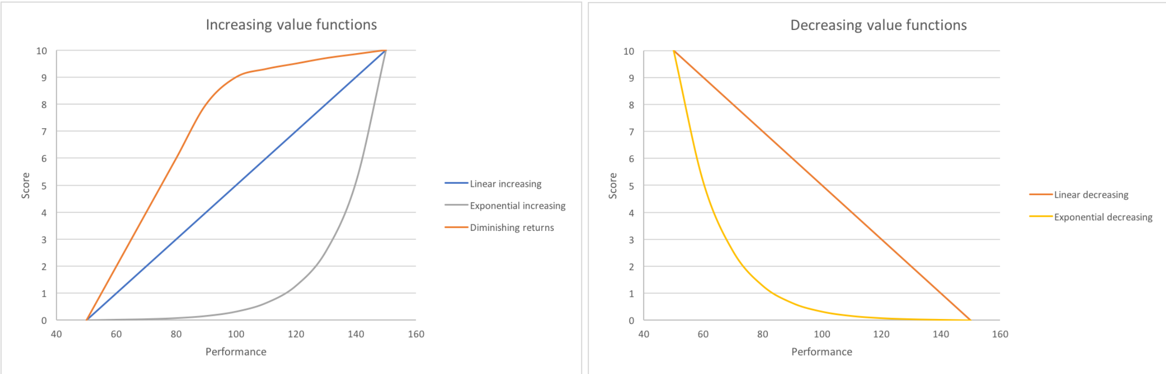
This study expresses scores on a conventional interval scale to allot a value score to each criterion, with a range between 0 and 10. The establishment of the interval scale can be done in two ways, using global or local scaling. With global scaling, a score of 0 (zero) is assigned to represent the lowest level of performance expected in the type of decision and 10 is assigned to the highest expected level. With local scaling, 0 is assigned to the worst performing alternative, and 10 to the best performing alternative. The advantage of global scaling is that it allows more alternatives to be added in a later stage, without influencing the scoring scales.

Although the choice between local and global scaling should make no difference to the ranking, it has an effect on the total score which is obtained by multiplying scores with weights (executed in later steps). Global scaling "therefore lends itself less easily to the construction of relative weights for the different criteria" [14]. Because it was considered likely that concepts were added or adjusted in later stages, this disadvantage was accepted and global scaling was chosen.

When the interval is established, three methods were considered to assign scores:

1. Specification of a value function
2. Direct rating
3. Indirect scoring

The first approach defines a value function to translate the performance value to a score. For most practical purposes, the shape is assumed to be linear. But in some cases, such as when there are thresholds above which further increments in improvement are less appreciated than below (diminishing returns), a non-linear shape may be preferred. An important benefit of this method is that drafting the shape of the value function is a useful exercise to force the designer to rethink and make explicit his assumptions. Some examples of differently shaped value functions are given in figure 4.4.



(a) Examples of increasing value functions (b) Examples of decreasing value functions

Fig. 4.4 Examples of various value function shapes for arbitrary performance values

The second approach, direct rating, is often used if time and resources are scarce and if metrics are not well-defined or agreed upon. The method prescribes assigning scores to the performance of alternatives, based on expert judgement. The method is intuitive and fast, but less insightful because it makes the value judgements less explicit compared to the value function approach. Furthermore, it is important to check consistency of scores, which is not necessary in the previous approach if the value function is agreed upon.

The third approach, indirect scoring, uses pairwise comparisons to assign scores. Examples of methods which use this strategy are the Analytic Hierarchy Process (AHP), REMBRANDT and MACBETH. These programs are more time-intensive than previous two methods were therefore not considered suitable for this project.

Where possible, considering the time available for analysis and the quality of the input information, the value function approach was chosen to assign the alternatives' scores to the criteria. If too little quantitative information could be gathered and qualitative judgement was used, the direct rating method was used.

When all alternatives are scored at every criterion, this results in a score matrix equal in size to the performance matrix:

$$S = \begin{pmatrix} k_{11} & k_{12} & \dots & k_{1n} \\ k_{21} & k_{22} & \dots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{m1} & k_{m2} & \dots & k_{mn} \end{pmatrix}$$

Where k_{ij} is the score of the i-th alternative on the j-th criterion, n is the number of criteria and m is the number of alternatives.

4.4.2 Comparison & Ranking

As was presented in figure 4.3, two methods were used in the attempt to find the 'best' configuration, which can be seen as complementary. On the one hand, the alternatives were mapped from the decision space to the criterion space to search for sets of well-performing alternatives [3]. On the other hand, the alternatives were ranked using MCDA techniques. Both methods are shortly described below.

4.4.2.1 Criteria mapping

For a particular decision problem, the decision space is defined by a set of decision variables and is typically limited by a set of constraints, which determines the set of feasible alternatives [44]. For each feasible alternative in the decision space, there is a corresponding mapping into the criterion space (see figure 4.5). The criterion space helps to evaluate the outcome of the decisions, by plotting the utility assigned to the performance with respect to the criteria on the axes. In other words, it allows an *'a posteriori'* articulation of preferences. This enables the search for non-dominated [4] solutions. The mapping illustrated in figure 4.5 gives visual insight in important trade-offs, while MCDA methods often produce a ranking based on numbers that is less insightful but easier to act on.

It must not be expected that in a complex decision process just one non-dominated solution is found. Besides, the search for non-dominated solutions is challenging and not always successful, especially if there are more than two criteria. If that is the case, the method is likely to identify subsets of well-performing alternatives, but cannot provide a definitive answer. To help make this decision, MCDA methods can then be used as a complementary tool.

[3]The decision space is "a representation of the individual decision variables", while the criterion space "represents the performance of the solutions in terms of the criterion outcomes" [44].

[4]Dominance occurs when one option performs at least as well as another on all criteria and strictly better than the other on at least one criterion. Non-dominated solutions are also referred to as Pareto-optimal solutions.

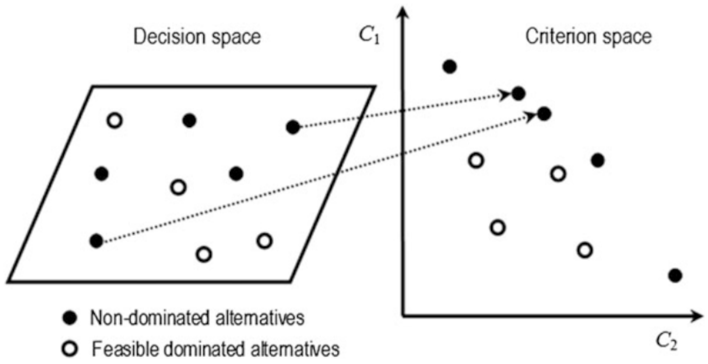


Fig. 4.5 Non-dominated alternatives in the decision and criterion space of a discrete multicriteria decision problem [44]

4.4.2.2 Multiple Criteria Decision Analysis

This subsection explains the use of MCDA methods and highlights the series of steps that are followed to arrive at a ranking of alternatives. In this context, ranking is defined as the activity of aggregating the scores assigned to criteria, with the aim to obtain an order of preference based on the overall performance of the alternatives. This requires assigning weights to the criteria, which signify the relative importance of one criterion with respect to another.

The MCDA procedure consists of the following steps:

1. Determine subjective weights of criteria
2. Determine preference order of alternatives
3. Analyse sensitivity

The steps are further explained below.

Step I: Determining subjective weights of criteria

This step entails assigning weights to the criteria scores, which requires the choice of a weighting method. Similar to the scoring methods, weighting methods also distinguish between local and global procedures [44]. The most commonly used methods are global procedures: ranking, rating and pairwise comparison. This study uses both the ranking and rating procedure. Pairwise comparison is considered effective but very time-intensive if performed thoroughly and was therefore omitted.

The *ranking method* is a simple method, which dictates to rank the criteria in order of the DM's preference. Criterion weight is then determined using:

$$w_k = \frac{n - p_k + 1}{\sum_{k=1}^{n} n - p_k + 1} \tag{4.1}$$

where w_k is the k-th criterion weight, n is the number of criteria under consideration (k = 1,2,...,n), and p_k is the rank position of the criterion [44] .

The *rating method* prescribes to estimate the criterion weights by assigning a score on a predetermined range. The DM rates the criteria according to their relative importance, after which the final weights are obtained by normalization.

$$w_k = \frac{s_k}{\sum s_k} \tag{4.2}$$

where w_k is the k-th criterion weight, s_k is the score assigned to the $k-th$ criterion

Despite the different ways of assigning the weights, all sets of weights meet the condition $0 \leq w_k \leq 1$ and $\sum_{k=1}^{n} = 1$. In addition, they must be ratio-scaled: if criterion C_1 is twice as important as criterion C_2, then $w_1 = 2 * w_2$. "Ratio-scaling ensures that the weights represent the trade-off that one is willing to make" [44, p. 37].

Step II: Determine preference order of alternatives

The previous step is most important and requires most input from the decision maker. To determine a preference order of alternatives requires aggregation of the multiple criteria using the weights obtained in the previous step, which is then "merely a matter of algorithmic and mathematical skills" [26]. From here, it is as if the outcome of the decision is put from the hands of the DM into the hands of someone else.

This work follows the weighted sum MCDA method, which is justified by the assumption of compensatory criteria [22] [67]. The weighted sum aggregation procedure derives its name from the fact that the global performance of an alternative is computed as the weighted sum of its evaluations along each criterion. This method requires *a priori* articulation of preferences and is characterized by its simplicity, which promotes transparency.

For each alternative, the total score is simply calculated as:

$$S_t = \sum S_k * w_k \tag{4.3}$$

where S_t is the total score, S_k is the alternatives' score on the k-th criterion, w_k the criterion weight.

Assuming that the obtained set of weights accurately represents the relationships between the criteria, the total score results in the ranking: the alternative with the highest score is supposed to be the 'best' one.

Step III: Sensitivity Analysis

To study uncertainty of the acquired ranking, sensitivity analysis is carried out. Two types of sensitivity analysis were conducted, which are shortly outlined below:

Mathematical sensitivity analysis

First, the more simple and most commonly used 'mathematical' sensitivity analysis was used. This involves varying the weight of one parameter while keeping the ratio of others constant. This makes the approach easy to implement and relatively easy to analyse. It may help indicate parameters which have a large impact on the final decision. However, this approach has limitations. First, the validity of the assumption that the ratio of other weights remains constant is debatable. How would the final outcome change, if two parameter weights would be large, and the rest very small? Second, if two alternatives are performing well without a clear winner, how can we justify opting for one over the other? To address these questions, stochastic methods can be used which vary all weights simultaneously.

Stochastic sensitivity analysis

Two stochastic sensitivity analysis approaches were used to study the robustness of the decision. The first method was proposed by Butler et al. [10]. It is based on Monte Carlo simulations, sampling all weights simultaneously from the same uniform distribution. In this study, that translates to the assumption that the DM has no obvious preference for one criterion over another. According to Butler, this method is effective in identifying sets of superior alternatives, and may eliminate the need for formal weight assessment.

However, in many cases, it is desirable to incorporate obvious differences in the DM's preference. Therefore, an improved methodology was implemented, proposed by Hyde, which incorporates three main improvements: [28]

1. Weights are varied around a pre-specified mean to search for solutions in the expected weight range, capturing DM preference.
2. Different distribution types can be specified. For a large uncertainty, a uniform distribution is recommended. When the DM is more certain, a normal distribution may be used.
3. Scoring values are also randomly sampled to account for uncertainty in the performance values and/or scoring methodology

The strategy and steps for stochastic analysis are given in figure 4.6.

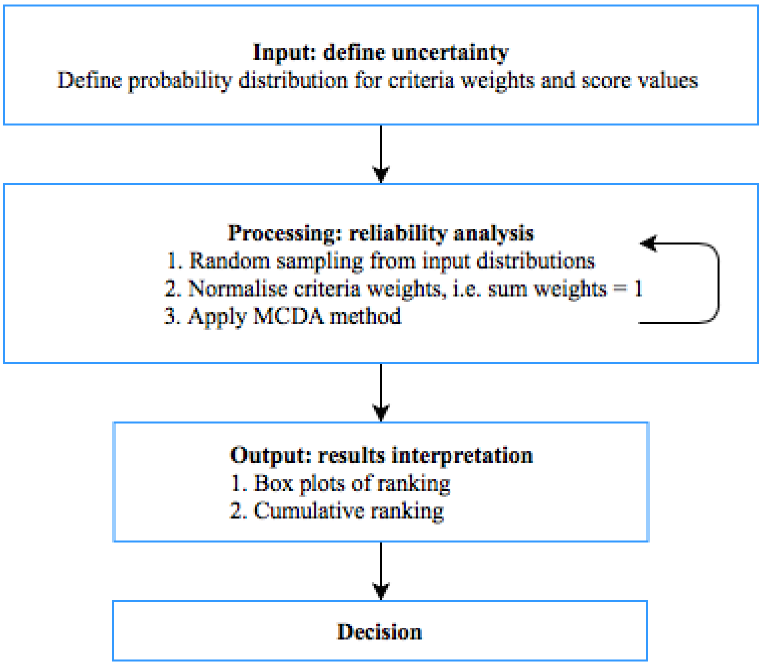


Fig. 4.6 Stochastic sensitivity analysis strategy, modified from Hyde [28]

Chapter 5

Conceptual Design - Results

This chapter treats the execution of the methodology outlined in Chapter 4. Section 5.1 treats the high-level design goals and requirements. Section 5.2 categorises existing concepts and presents a selection of new concepts. Configurations of these concepts are created in order to scale to farm level, presented in section 5.3. The evaluation, comparison and ranking following the decision-making framework is discussed in section 5.4. The selection of the most preferred concept and the limitations of the method are topic of discussion in section 5.5.

5.1 Design goals and requirements

This section presents high-level design requirements which form the basis of the concept exploration phase. During the drafting of concepts, more requirements emerge and the list is extended. Eventually, this leads to the more detailed evaluation framework explained in section 5.4.1.

While drafting requirements and design goals, there exists a trade-off between requirements that are too vague and those that are so detailed that they take a long time to produce. Formulating requirements in too much detail from the start can both restrict the creative process and prevent good concepts from being formed as well as prematurely eliminate solutions which do not meet all requirements.

The first step towards formulating the goals and requirements of a design is to identify key stakeholders. The relevant stakeholders in aquaculture projects have been studied by Shainee et al. [58] and were categorized into three groups: *society*, *the fish farmer* and the *fish*. These can be broken down into more detailed types of institutions, companies and groups of people, but in the early stage it is felt that three groups suffice. For wind energy, it is useful to adopt a similar categorisation, and the stakeholders are defined as *society* and the *wind farm operator*. The challenge of a multi-use platform is that it needs to satisfy the requirements of four stakeholders (wind farm operator, salmon farmer, society, fish) while single-use concepts can focus on two or three. It is therefore likely that concessions will have to be made.

The overall high-level requirements of the design then follow from analysing the requirements set by the different stakeholders, which are segmented in figure 5.1. Organising requirements in such a tree-shaped diagram helps structure the analysis. The complete version is added in Appendix B.

The shared requirements are particularly interesting, because they offer the potential for synergies. From society perspective for instance, involved in both the aquaculture and wind energy component, the MUP design must be primarily effective in solving societal issues such as a shortage of space, pollution and noise. Besides, it should minimize interference with other industries, such as local fisheries. Furthermore, cost-effectiveness is a dominant requirement from both sides, leading to lower-level objectives such as high-energy yield, good salmon growth conditions and low maintenance costs.

The high-level objectives serve as input for the first round of brainstorming innovative concepts. As that process progresses, more requirements are identified and added to the issue tree.

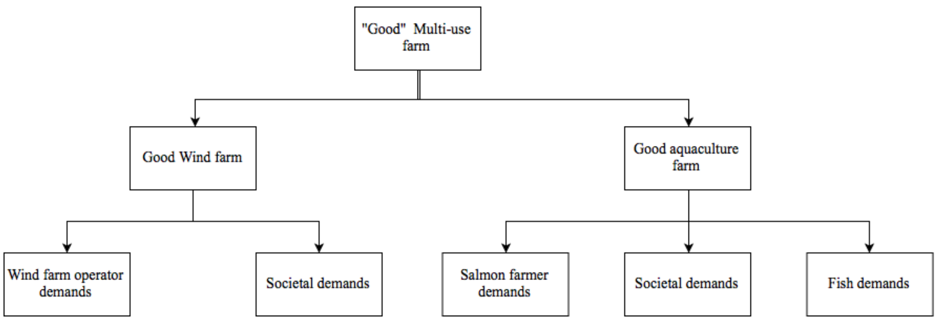


Fig. 5.1 First level of issue tree which segments what constitutes a good farm into stakeholder demands. The full version of this figure is given in Appendix B

5.2 Concept study

This section presents a concise analysis of existing configurations and subsequently presents eight new concepts which were created during this research.

5.2.1 Categorising existing configurations

Categorizing existing configurations helps to identify concept-specific (dis-)advantages, which contributes to early-stage design choices and is considered useful for organising the discussion. From the existing projects shortly addressed in section 1.2, we can distinguish various types of solutions.

First, it is useful to specify the terminology. A distinction is made between "core concepts", "concepts" and "configurations". To the group of core concepts belong the stand-alone references, that is those structures used for either wind energy or aquaculture. The term concepts describes multi-use platforms which host both activities. Finally, a configuration relates to the farm level, and can be a combination of concepts and/or core concepts.

The MERMAID project features (stand-alone) aquaculture units situated in between the (stand-alone) wind turbines, utilizing the space within the wind farm without being integrated into the same structure. Hence, it can be described as a configuration which is based on core concepts. This illustrates the type of configurations which fit into the "share space" category, which is illustrated as separate branch in figure 5.2.

The second branch captures those platforms which integrate aquaculture and wind energy in the same platform, instead of between the platforms. Examples of such platforms are the TROPOS or H2OCEAN conceptual designs. At this level, each category offers distinct advantages and disadvantages, listed in table 5.1.

Then, within the share platform category, we can differentiate between modular concepts as demonstrated in the TROPOS project and fully integrated concepts as presented by H2OCEAN & Wei He.

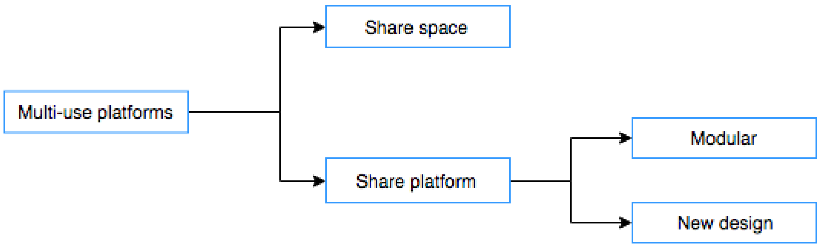


Fig. 5.2 Classification of multi-use concepts

Table 5.1 Concept-specific advantages and disadvantages

	Advantages	Disadvantages
Share space	- Lower level of coordination required between operators - Flexibility - Experience with design, although this would need modification for exposed environments	- Installation is more difficult - Navigation issues - Likely to be more expensive due to high mooring costs
Share platform	- Fewer navigation issues - Possibility to share support structure costs - Fewer crew transfers required	- More complex design - Higher level of coordination required between operators

5.2.2 Generating new concepts

This section presents a selection of eight new concepts. Based on the comparison in table 5.1, it was chosen to focus solely on "shared-platform" concepts, because it is expected that they maximize the potential sharing benefits and are more challenging from engineering perspective. Besides, the stand-alone core concepts can that be used for "share-space" configurations can be drawn from a much larger pool of existing core concepts. Lastly, it is felt that the results and recommendations which follow from studying "shared-platform" concepts can trickle down to "shared-space" configurations, but not vice versa.

Sketches of the newly generated concepts are displayed in figure 5.3 and a description and an indication of their size are given in table 5.2. This section is limited to the presentation of the concepts. The evaluation will be presented in section 5.4.1.

Table 5.2 Cage volume estimations and installed power per platform

Concept	Description	Estimated cage volume [x1000 m^3]	Installed capacity [MW]
1	Spar-buoy + floating circular net-pen	77	10
2	Spar-buoy + submersible cage	48	10
3	Hexicon-platform + floating circular net-pen	164	20
4	Hexicon platform + fixed copper netting	144	10
5	Closed cage floating structure	20	10
6	Hexagonal platform + fixed netting	678	30
7	Three-turbine platform + flexible netting	1000	30
8	Four-turbine platform + fixed netting	2000	40

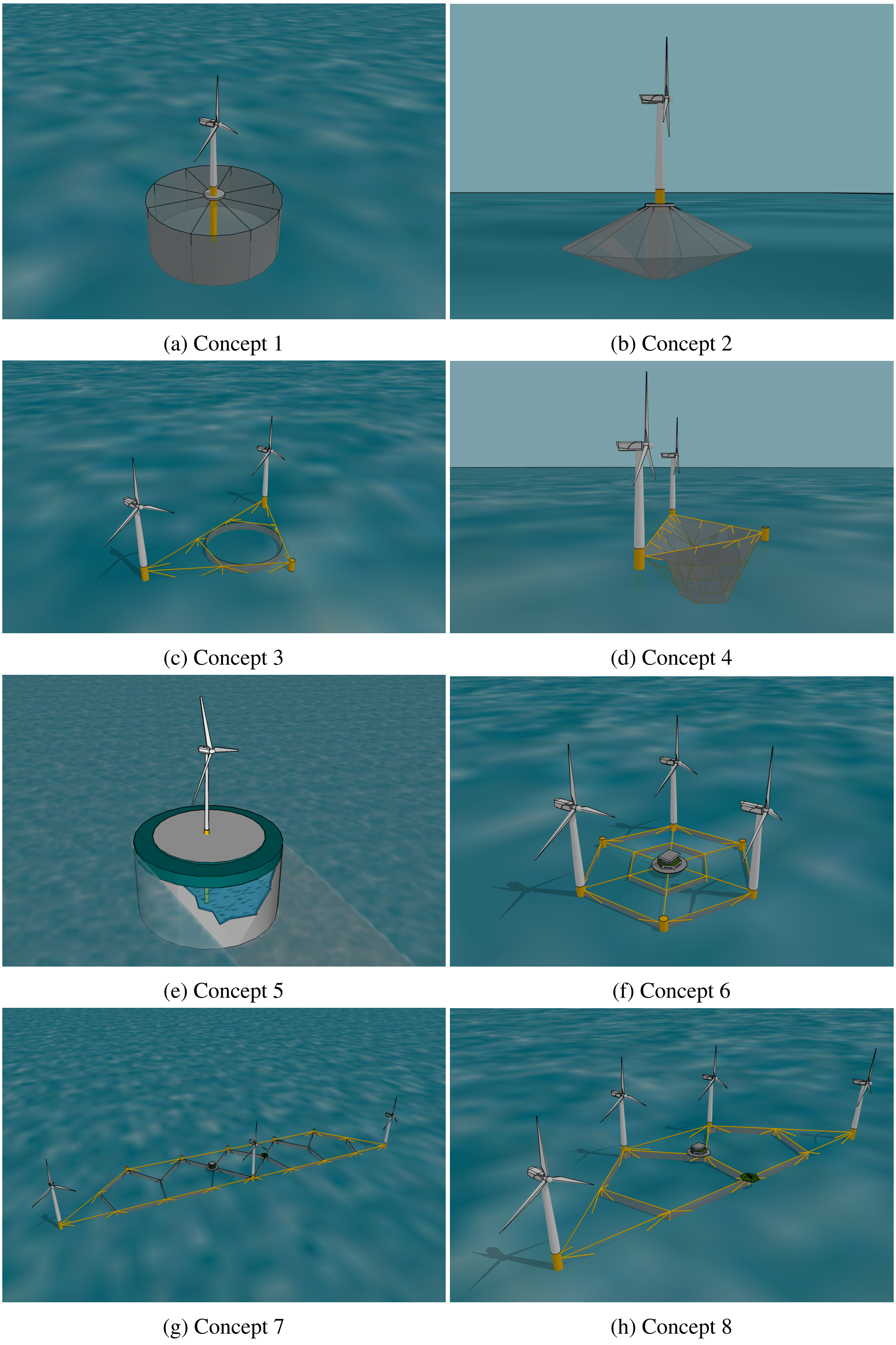


Fig. 5.3 Multi-use platform concepts 1-8

5.3 Creating configurations at farm level

To allow fair evaluation of concepts, they need to be integrated at farm level, which was discussed in section 4.3.1. It was explained that the number of multi-use concepts required to reach the aquaculture production capacity is lower than that to reach the wind energy capacity. For that reason, the first step in forming a configuration is to take as many multi-use platforms as required to meet the aquaculture demand. Subsequently, the multi-use concepts are supplemented by existing single-use wind energy core concepts to reach the 800 MW target. The core concepts which were chosen are the spar-buoy and Hexicon platform.

Determining the composition of the configurations (named from A-N) then becomes a simple calculation. Figure 5.4 illustrates the composition of MUP and single-use platforms in each configuration. For more detailed insight, table 5.3 is provided.

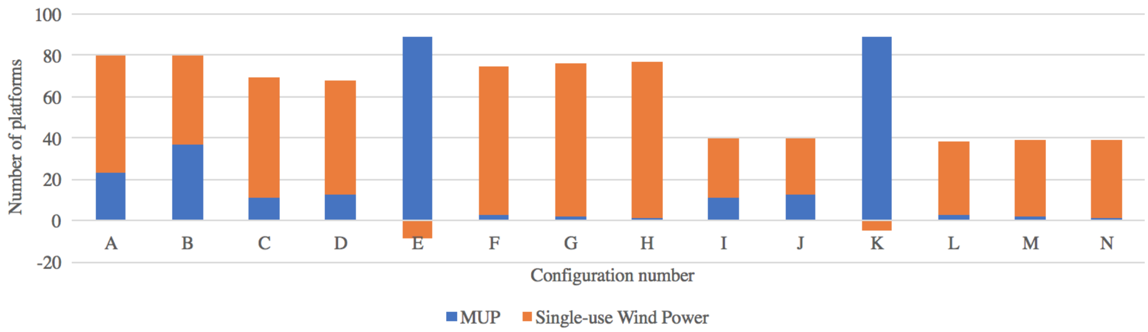


Fig. 5.4 Number of platforms per configuration

It may be useful to state once more that only the share-platform concepts are considered, and that share-space configurations are not evaluated. Moreover, from the existing share-platform concepts, only the H2OCEAN and TROPOS project offered a floating solution. The first concept is not considered because it is based on vertical axis wind turbines and limited specifications could be found. The latter concept is very similar to the newly created concept 3, but the main difference is that it is much smaller because it intends to generate electricity for local use instead of large-scale power generation. This concept is therefore not in line with the general design goals and requirements set out in the beginning of this research and is therefore not considered for the rest of the analysis.

Inspecting the composition of the configurations in figure 5.4, it is striking that configurations E and K are problematic. The cage volume of concept 5 is too small to reach the desired cage volume without reaching more than 800 MW. This could have been circumvented by slightly adjusting the case-study parameters, but this has not been done on purpose to highlight the poor flexibility of this concept with respect to scaling to farm level.

To solve this issue and proceed with the analysis, it is assumed that the closed cage volume can be made approximately 10% larger without major impacts to the concept. Effectively, this measure entails giving the concept the benefit of doubt, which should be noted but only needs to be further evaluated if the concept performs well in the next steps.
Not surprising, but worth noting, is that the addition of the Hexicon core concept allows a large reduction in the total number of platforms that is required.

Table 5.3 Composition of concepts within configurations A-N. Numbers indicate number of platforms

Concept	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	23													
2		37												
3			11						10					
4				12						12				
5					89						89			
6						3						3		
7							2						2	
8								1						1
supplemented by:														
single-turbine	57	43	58	55	-9	72	75	76						
multi-turbine									29	28	-4	36	37	38
Total	80	80	69	68	80	75	76	77	40	40	84	39	39	39

5.4 Evaluation, comparison and ranking

5.4.1 Evaluation

This section treats the evaluation of alternatives, covering the three main activities:

1. Identifying evaluation criteria and metrics
2. Measuring performance alongside the metrics defined in previous step.
3. Scoring: estimating the degree to which a decision-maker achieves utility from certain level of performance.

5.4.1.1 Identifying criteria

Initially, from talks with experts and inspection of peer-reviewed articles and grey literature such as annual reports, consultancy reports and presentation material, 12 criteria were distilled, tracing back to higher-level objectives as presented in figure 5.5. During the evaluation process, 4 criteria were discarded for failing the requirements, which are indicated with a red cross. In the next section all criteria are discussed consecutively, and the reason for omitting the four criteria will be further explained there.

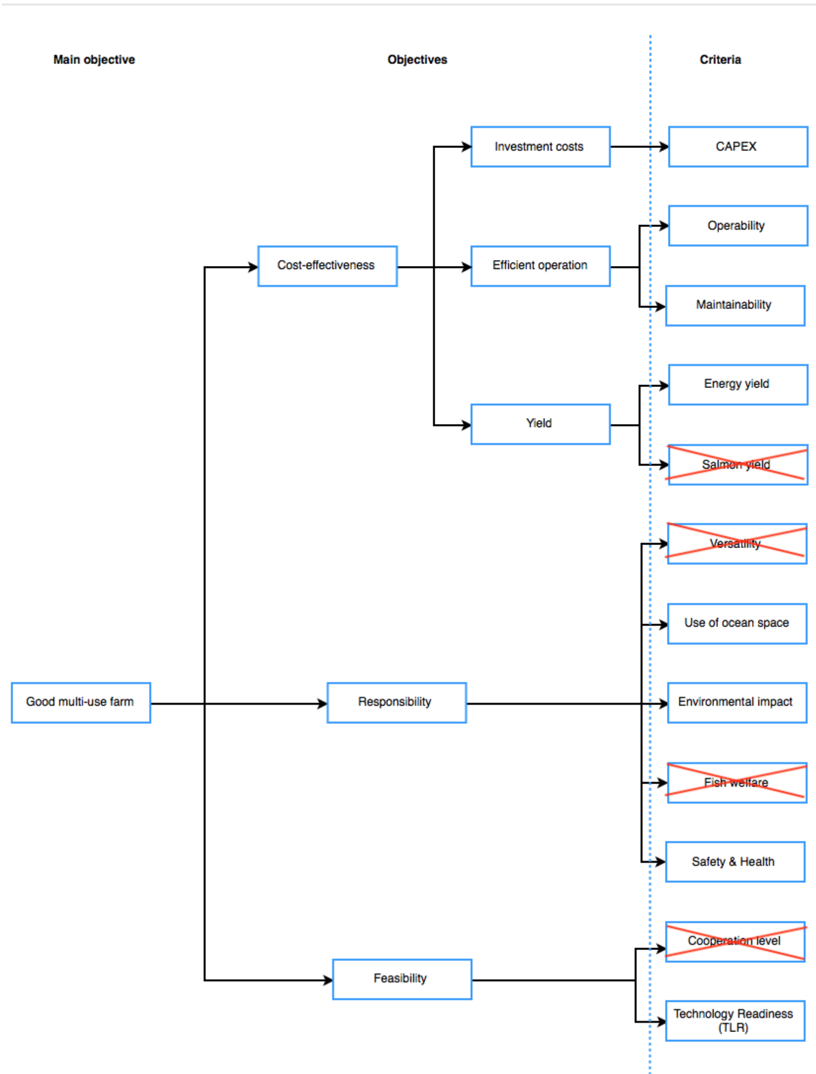


Fig. 5.5 Breakdown of evaluation criteria hierarchy. A red cross indicates a criterion is discarded.

5.4.1.2 Measuring performance and scoring

This subsection treats for every criterion its meaning and metrics, the alternatives' performance on these metrics and how this translates to a score. An overview and evaluation of scores follow at the end of this section.

CAPEX

The capital expenditure criterion aims to include costs associated to the purchase and commissioning of the platform in the decision-making process. The main drivers of capital costs for offshore floating wind energy are turbine costs, installation costs and support structure costs. Due to the limited experience with floating support structures in general, cost data of existing structures is scarce. Hence, estimating the costs of a novel concept structure inevitably leads to a coarse estimate.

An intuitive method to arrive at a best-estimate is to express the costs of the novel concept in terms of a percentage of the costs of a better known reference concept: the spar buoy. Due to absence of cost data, spar-buoy costs given in [31, p. 82] were used.

Table 5.4 provides the floater cost and installation costs estimates expressed in million euros, supported by the assumed multiplier values. The sum of both values is used as a quantitative metric for CAPEX, and when multiplied with the total number of platforms in a farm, allows comparison across configurations in figure 5.6.

These values translate to a score following a linear decreasing value function, defined in figure 5.7a.

Table 5.4 Cost estimations of individual concepts with respect to the spar-buoy (in million euros). Costs and estimations of spar buoy, Hexicon and concepts are largely based on reference data from [34], [49] and [31].

Cost type	Spar	Hexicon	1	2	3	4	5	6	7	8
Floater cost	3,2	7,04	3,36	3,36	7,3	8,32	4,16	9,6	11,2	16
multiplier (%)		220	105	105	225	260	130	300	350	500
Installation cost	3	1,8	3	3	1,8	1,8	3	2,4	2,4	2,4
multiplier (%)		60	100	100	60	60	100	80	80	80

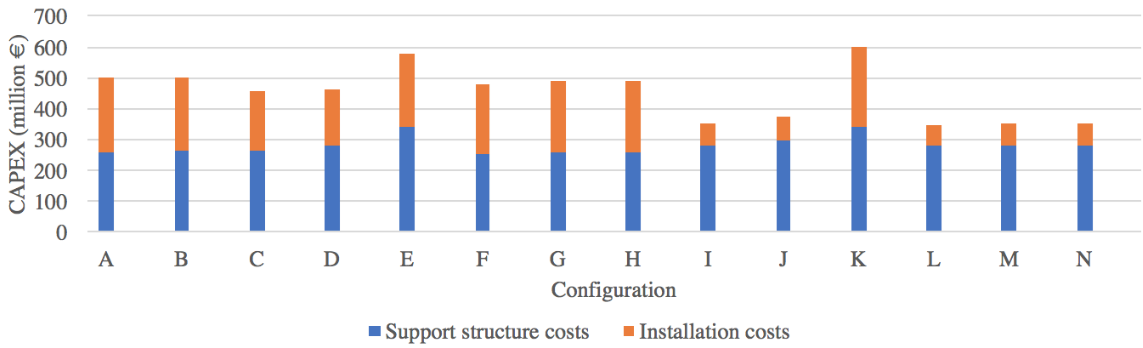


Fig. 5.6 CAPEX estimate for every configuration

Operability

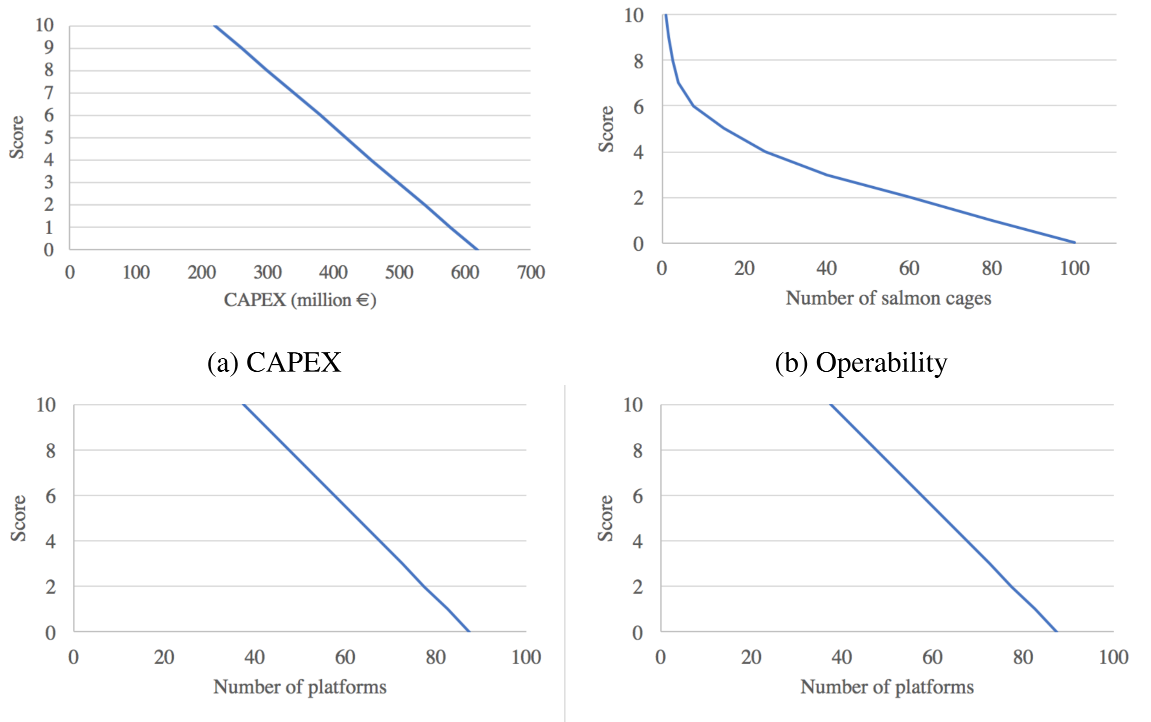
To operate and maintain a wind energy and/or aquaculture farm is an intensive task, split into various O&M activities. Whereas the maintenance part heavily dominates wind energy, the exact opposite is true in salmon aquaculture, which requires many more operational tasks. To distinguish between the two, this criterion refers solely to the ease of operation of the salmon farming activity.

The performance of the criterion operability has been evaluated as function of the number of salmon cages, and translates into a score by evaluating a non-linear decreasing value function shown in figure 5.7b. It is considered likely that the marginal utility of having fewer platforms is higher in lower ranges.

Maintainability

Whereas operability dominates the life-cycle needs of the aquaculture side, this criterion represents the wind energy side, for which wind turbine maintenance is a crucial activity.

The scoring procedure for maintainability is similar to previous criterion, but is based on the number of wind energy platforms that would need to be visited for repairs. The utility function is approximated as a linear decreasing straight line, given in figure 5.7c. Whereas aquaculture operations are routinely performed and each platform is thus visited on a routine basis, corrective maintenance of wind turbines is required only upon failure. In that case, having fewer platforms is not so much more beneficial.



(a) CAPEX (b) Operability

(c) Maintainability (d) Use of Ocean Space

Fig. 5.7 Utility functions

Energy yield

For the profitability of a wind farm, energy yield is an important criterion. Performance in this context is interpreted as a combination of the cumulative installed power capacity on the concepts within the configuration and the concept's ability to capture energy efficiently. Because it is impossible to quantify the difference with a reasonable amount of accuracy and with limited time, qualitative assessment is attempted. As a proxy for the ability to capture energy, the losses which occur through misalignment with the wind direction are used. This assumption favours small concepts, and especially single-turbine platforms, which are assumed to be most efficient.

First, to estimate the impact of potential losses, the share of installed wind energy capacity on the multi-use concepts is calculated with respect to the entire farm. It is assumed that the spar-buoy and Hexicon platforms, which serve as a supplement, do not influence the total energy yield. The difference between the configurations is then limited to the ability of the MUP-platforms to capture energy efficiently. One important area that needs more work to better analyse the impact on energy yield is the influence of the netting structure on the yawing ability of the platform. It is expected that a large netting structure, especially fixed copper nettings, induces higher drag and inertia and therefore reduces energy capture.

Table 5.5 summarizes the performance evaluation, which translate into a score using the direct rating method.

Table 5.5 Performance estimates for energy yield criterion. Inertia scoring:l = low, m = medium, h = high. Energy yield scoring: E = excellent, M = medium, S = satisfactory

Configuration	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Capacity (%)	29	46	27	31	100	10	7	5	27	31	100	10	7	5
Inertia			l	l		m	m	h	l	l		m	m	h
Performance	E	E	H	H	E	S	S	S	H	H	E	S	S	S

Salmon yield

This criterion is to the fish farmer what energy yield is to the wind farm owner. Estimating the yield of a salmon farm is a complex matter, for which no simple method was found. Important parameters that may vary across concepts include, but are not limited to: oxygen supply rate, stress levels associated with movement of the platform, the ability to feed the fish homogeneously and escape risk. In an interview, Professor Langan pointed out that he would prefer multiple small cages over a larger cage due to the associated risk of fish escape [40]. On the other hand, it was concluded that this risk could be reduced in larger structures by using a copper netting. All in all, at this stage, it is difficult to operationalise this criterion into a reliable metric and therefore it was chosen to leave this criterion out of the comparison analysis.

Versatility

This criterion attempts to evaluate at an early design stage the concepts future compatibility with other uses, during its life-time and beyond. It was found later that, although this point should be part of the design procedure, it cannot reasonably function as an evaluation criterion because it would rely on speculative claims which can hardly be verified. Furthermore, it is unlikely that accurate estimations can be made about the potential use of the platform after its life-cycle, say 20 years. Therefore, this criterion is not considered in the comparison.

Use of ocean space

One of the main reasons why research for multi-use platforms is funded is its potential to efficiently use ocean space. As a metric for area efficiency, the number of platforms is chosen. With that assumption, it is important to state that spacing between platforms is assumed equal. Only then do fewer platforms require less space. In reality, the spacing between multi-use platforms will be slightly larger with respect to single-use platforms due to wake effects.

The expected utility increase per unit area is assumed to decrease linearly with increasing space required, indicated in figure 5.7d

Environmental impact

The potential to reduce impact on the environment is the second reason why research for multi-use platforms is stimulated. These benefits are primarily observed from holistic perspective. Analysing in more detail the wind energy activities, no environmental benefits are expected that can distinguish between the concepts. The aquaculture side offers more ground for comparison.

Fish escape risk, interaction of farmed species with wild species, and waste from the farm are the parameters listed most. The latter two parameters depend on whether the cage is closed or open. Indicators for fish escape risk are on the one hand the probability of escape, determined by the structure type, and the severity of the event, determined by the size of the cage.

Table 5.6 lists the performance of the alternatives on the sub-criteria. Estimating the risk of fish escape is troubling, but how to weigh that against the other component (wild species interaction) to reach a final score is even more difficult. Due to the limited information available, intuition is used to obtain a best-estimate.

Table 5.6 Metrics of environmental impact. O = open, C = closed. ++ is very high, + = high, 0 = moderate, - = low, - - is very low

Configuration	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Cage type	O	O	O	O	C	O	O	O	O	O	C	O	O	O
Fish escape risk	+	+	+	0	- -	0	+	++	+	0	- -	0	+	++

Fish welfare

Fish welfare should not only be considered for obtaining a high production level, there are also ethical aspects that require the attention of the DM. Respecting fish welfare is, in the eyes of the author, a part of our moral responsibility. This report will not address this matter in detail, but points to the fact that fish welfare should be part of the integral design process. Whether fish farming is sustainable and morally acceptable is still topic of debate and requires more attention.

Measuring fish welfare is not straightforward, but several parameters are known to impact it, for instance: movement of the cage, frequency of inspection, oxygen supply, distribution of nutrients and food and deflection of netting which compromises their space [58]. Based on the information available, no supporting arguments can be found to distinguish between the ability of the concepts to promote fish welfare [40]. Therefore, the criterion has been removed from the decision-making procedure for failing the operability criterion.

Safety and Health

Safety is one of the most important requirements in any offshore activity. In this context, the criterion aims to capture the relative increase in safety level that can be achieved with a certain configuration, anchored in the belief that all concepts pass a certain threshold level[1]. It is then attempted to distinguish between structures that have the potential to ensure better safety through fewer required crew transfers and higher stability.

Next to that, the criterion evaluates the level of comfort a configuration can offer the crew during their period offshore, and aims to cover health-related factors such as preventing sea-sickness and long journeys.

It is thought that some configurations can perform better given these parameters, summarized in table 5.7. Intuitive assessment is used to translate the performance into a score (see table 5.10).

Table 5.7 Metrics of safety. ++ is very high, + = high, 0 = moderate, - = low, - - is very low

Configuration	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Accommodation	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Stability	- -	- -	0	0	-	+	++	++	0	0	-	+	++	++
Nr. of transfers	++	++	+	+	++	+	+	+	-	-	++	- -	- -	- -

Cooperation level

This criterion is meant to give an indication of coordination that is required throughout the design and operation of the farm and platforms. Shared-space concepts (section 5.2.1) do not require cooperation in the first engineering sketches and concept development. Because they are more independent than the shared-platform concepts, they are likely easier to realise. In contrast, a shared-platform concept requires coordination from the start, from the drawing table to the installation, which may form a barrier for their development. Because this study

[1] This assumption is required to maintain criteria which are compensatory, which in turn is a critical assumption to justify the use of weighed-sum aggregation as MCDA procedure

focusses on shared-platform concepts only, this criterion is eliminated from this particular decision-making process.

Technology Readiness

The last criterion gives a measure of the experience with the technology, giving an idea about the maturity of the concept. To assess the technology readiness, a qualitative 5-stage scale is used, displayed in table 5.8.

Table 5.8 Technology readiness metrics, adapted from [50]

Score	Description
1	**Basic principles observed and reported** Scientific research begins to be translated into applied research and development. This stage is characterized by mapping out requirements and desired functions of the technology.
2	**Technology concept and/or application formulated** Analytic studies and in-depth investigations of principal design considerations. This stage is characterized by concept exploration.
3	**Proof of Concept** Component and/or partial system validation. This stage is characterized by computer simulation or laboratory experiments.
4	**System prototype demonstration** Includes system integration and involves a demonstration of the technology in its almost final form. Characterized by testing in site conditions similar to the desired site and includes final design elements.
5	**Successful system operational** This stage involves commercialized units, service qualified and is characterized with years of successful operation.

Because the concepts are all new, all would obtain the lowest score when analysed as a whole, losing the criterion's differentiating capability. For that reason, the technology readiness of the wind energy support structure and aquaculture technique are evaluated separately. Evaluating these judgements allows to construct an idea about the technology readiness of the whole.

The sum of the separate scores may serve as an indication for the final score. However, the utility obtained by going up one level in technology readiness is not the same for every stage. For instance, when one configuration receives score 3 + 3 = 6 and another receives 2 + 4 = 6, this does not mean their technology readiness is equal [2]. Such cases should be evaluated in more detail, and may be intuitively adjusted by the DM during final scoring.

Table 5.9 Technology readiness assessment

Configuration	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Wind Energy	5	5	3	2	1	1	3	2	3	2	1	1	3	2
Aquaculture	5	4	5	3	3	4	3	3	5	3	3	4	3	3

Table 5.10 Score of configurations A-N on the eight evaluation criteria

Configuration	A	B	C	D	E	F	G	H	I	J	K	L	M	N
CAPEX	3	3	4	4	1	4	3	3	7	6	0	7	7	7
Operability	2	1	5	6	1	8	9	10	5	6	1	8	9	10
Maintainability	0	0	4	4	2	3	2	2	10	9	1	10	10	10
Energy yield	10	10	9	9	10	5	5	1	9	9	10	5	5	1
Use of ocean space	1	1	4	4	2	3	2	2	10	9	1	10	10	10
Environmental impact	3	3	3	5	10	5	3	0	3	5	10	5	2	0
Safety	0	0	3	3	2	4	5	5	6	6	0	8	10	10
Technology readiness	10	9	8	5	3	4	7	6	8	5	3	5	7	5

[2] In hindsight, the score values obtained should lie further away from eachother. The utility of a category 5 technology is more likely to be 100 times more than a category 1 technology than just 5 times more.

5.4.1.3 Overview and evaluation of scores

The scores for each criterion are listed in table 5.10, which has the shape of the transpose of the score matrix explained in section 4.4.2.2.
It is important to check the scoring values and evaluate the relevance of the criteria before moving to the next stage. The attributes defined by Keeney and Raiffa, outlined in methodology section 4.1.4.1, were used to assess the criteria. While evaluating the alternatives, failure to comply to the attributes led to the elimination of four criteria from the comparison. The non-redundancy attribute can only be evaluated when all scores are assigned, hence the compliance of the set of scores to this attribute is treated here.

To assess the remaining 8 criteria on the non-redundancy attribute, their correlations were studied, presented in figure 5.8. When criteria are correlated, the two variables fluctuate together, which can show in the graphs as a straight line [3].

As expected, the criteria ‘Use of ocean space’ and ‘Maintainability’ show a strong positive correlation caused by the dependency on the number of platforms. This suggests the criteria are redundant and that they should be merged into one criterion. However, although a correlation is observed, it is believed that in this particular case, the correlation does not mean the criteria are redundant. They are seen as independent criteria which happen to depend on the same metric, although ideally, better suited metrics would be used to more accurately represent each criterion.

[3] Note: expecting a straight line assumes a linear correlation, which is not necessarily true.

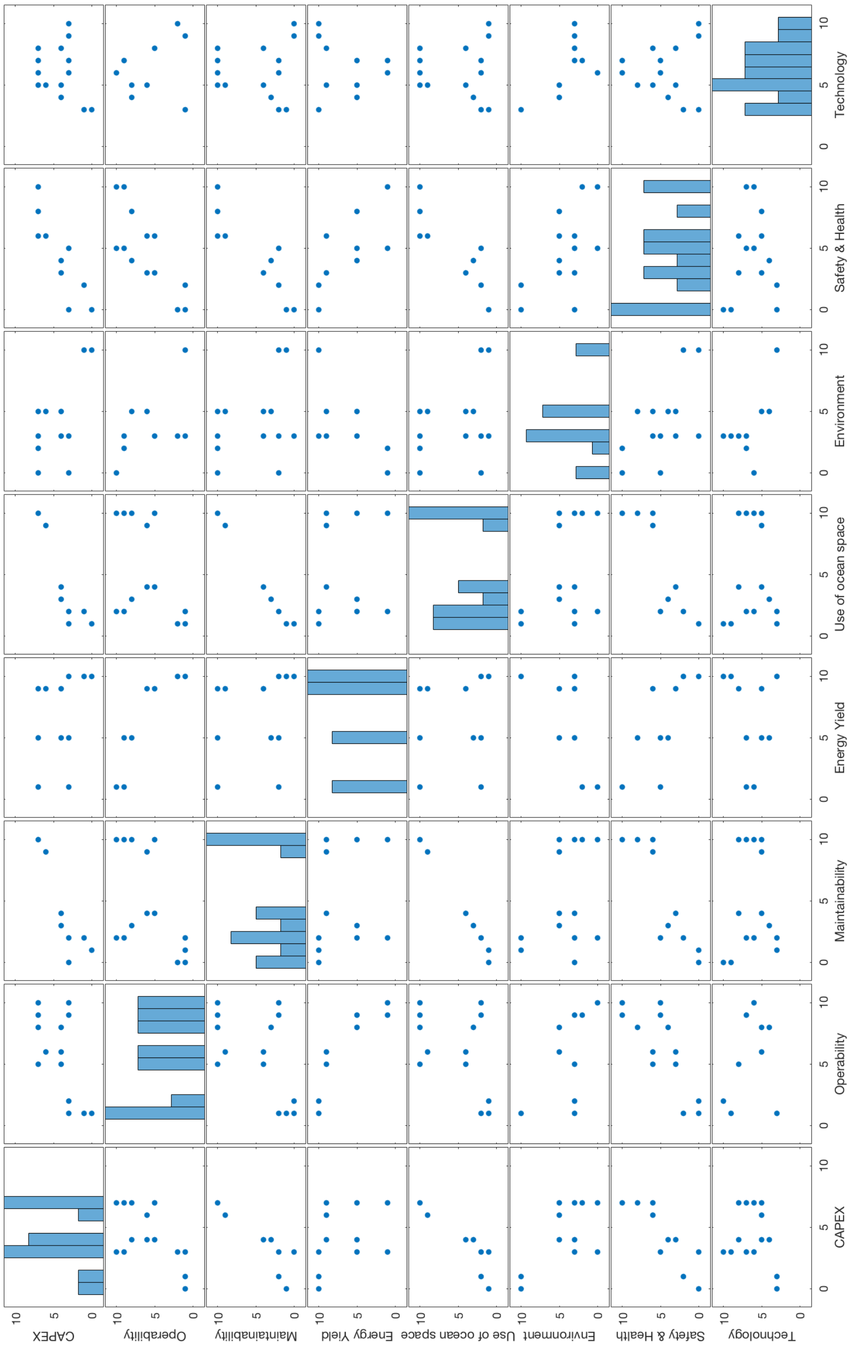


Fig. 5.8 Correlation between criteria. Each dot represents the score of one concept on a particular criterion. The bar-charts give an indication of the distribution of the scores within their respective ranges.

5.4.2 Comparison & Ranking

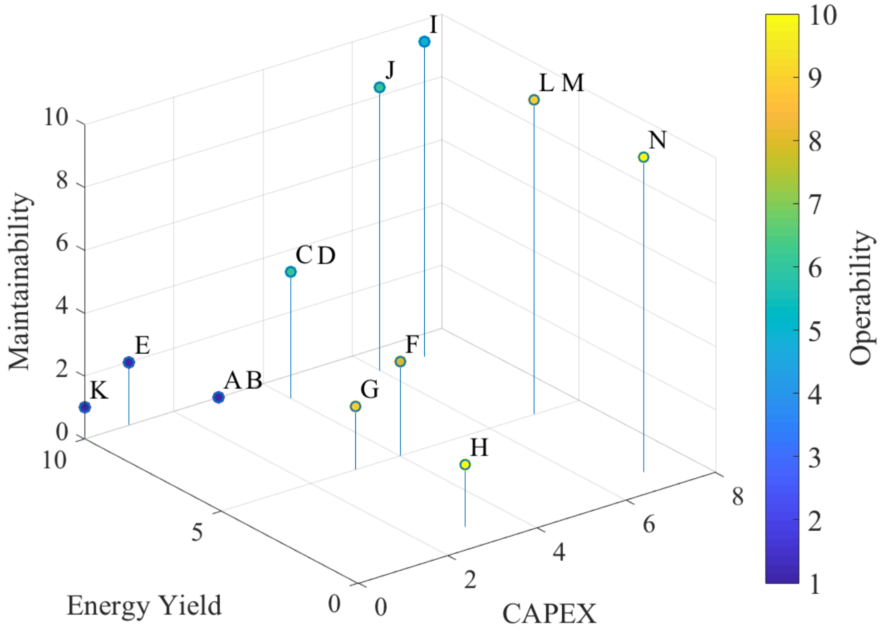
The activity of choosing the ‘best’ alternative involves making an assessment of the trade-offs between criteria based on the decision maker’s preference. This section treats first the visual representation of scores, or criteria mapping, which is useful for evaluating trade-offs and identification of sets of superior alternatives. Subsequently, aimed at identifying the single ‘best’ configuration, the results of the MCDA method will be presented, complemented by sensitivity analysis.

5.4.2.1 Criteria mapping

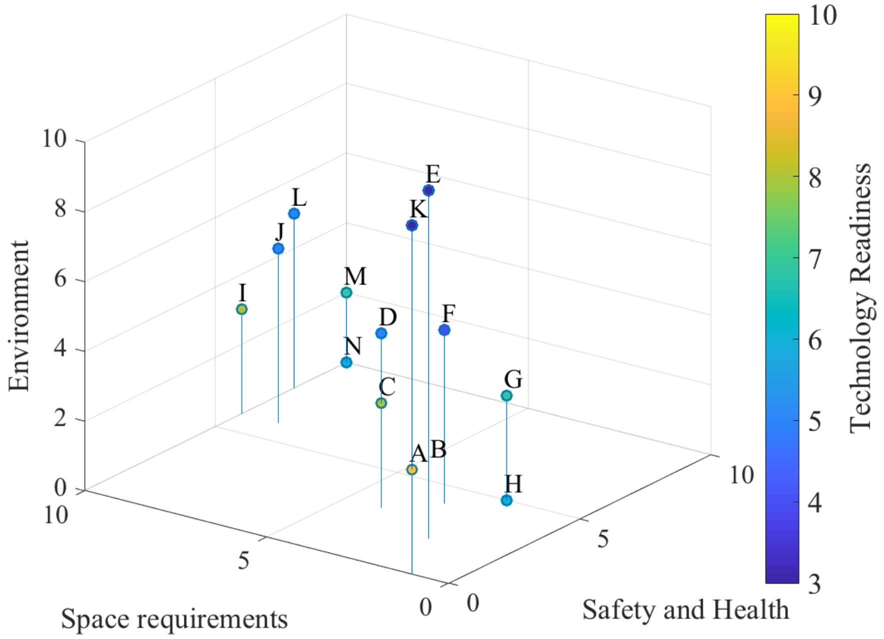
Figure 5.9 visualises the scores of the alternatives on all 8 criteria in just two graphs. Note that the coloured bar which represents one of the criteria is less dominant in this type of visualisation. If unaware, this may cause the reader to attach less weight to that criterion. Besides, if the scores of two base-plane criteria coincide, the fourth ‘dimension’ is not displayed correctly, requiring the DM to inspect this criterion in more detail. These disadvantages are important to note, but did not outweigh the advantage of being able to compare four criteria in one figure. In some instances, for example when two particular conflicting criteria are found, a 2D plot can lead to more insights.

Inspecting figure 5.9a, it seems configurations M,L,J and I are superior candidates. Although scoring higher on operability, candidates M and L perform relatively poor on criterion energy yield with respect to I and J. Inspection of figure 5.9b strengthens the view that the same set is superior, but emphasises that alternatives E and K score better on environment. This is caused by their closed-cage aquaculture design.

Inspecting both figures, is seems that within the bigger concepts, alternative M outranks N and is on par with alternative L. Within the smaller concepts, alternative I seems to outrank J. Although a set of superior alternatives has been identified, it is unclear which would be the most preferred. When there are many criteria and alternatives, an *a priori* articulation of preference, involving formal weight assessment, may help to obtain additional insights. This will be discussed in the next section.



(a) Criteria 1-4



(b) Criteria 4-8

Fig. 5.9 Mapping of scores to the criterion space.

5.4.2.2 Multiple Criteria Decision Analysis

This section treats consecutively the three steps that constitute the MCDA framework which was presented in section 4.4.2.2:

1. Determine subjective weights of criteria

2. Determine preference order of alternatives

3. Analyse sensitivity

The steps are detailed below.

Step I: Determine subjective weights of criteria

Evaluating the DM preference for one criterion over another is necessary to identify a single best alternative. Because the decision outcome can be largely influenced by the DM preference, different stakeholder perspectives are evaluated: the *operator* and *society*. Both the rating and the ranking method are applied for both perspectives.

The operator's preference is obtained by consulting Niklas Hummel, senior engineer at Hexicon, and presented in table 5.11 [4]. Society's preference values (listed in the lower table) are assumed by the author and assign more weight to criteria which are directly beneficial to society such as environment and use of ocean space.

Table 5.11 Scoring and ranking of criteria, with corresponding weight factors, from operator perspective (top) and society perspective (bottom)

Operator preference	Rating		Ranking	
	Score (1-10)	Weight	Rank (1-8)	Weight
CAPEX	8	0,27	2	0,19
Operability	3	0,10	3	0,17
Maintainability	3	0,10	4	0,14
Energy yield	9	0,30	1	0,22
Use of ocean space	1	0,03	6	0,06
Environment	3	0,10	7	0,11
Safety & health	1	0,03	8	0,03
Technology Readiness	2	0,07	5	0,08

[4] Numbers may not add up to 1 and/or satisfy the ratio-scaling criterion due to rounding, which is used for presentation.

Society preference	Rating		Ranking	
	Score (1-10)	Weight	Rank (1-8)	Weight
CAPEX	5	0,12	4	0,14
Operability	3	0,07	6	0,08
Maintainability	3	0,07	7	0,06
Energy yield	3	0,07	5	0,11
Use of ocean space	9	0,21	2	0,19
Environment	10	0,23	1	0,22
Safety & health	9	0,21	3	0,17
Technology Readiness	1	0,02	8	0,03

Step II: determine preference order of alternatives

In this section, the scores are aggregated by multiplying them with the corresponding weights, using the weighted-sum MCDA method. The total scores allow to rank the alternative in order of preference. Table 5.12 and 5.13 present the rankings for the operator and society preference respectively.

First, it can be observed that from both perspectives, the alternatives I, J, L and M constitute the top of the list. Note that the same sub-set was identified in the previous step, during mapping of requirements.

Second, it is evident that the two weight assessment methods can yield different rankings. From operator perspective, the top-pick is the same (alternative I) for the two weighting methods, but the second, third and fourth place are not. Apparently, the method of assigning weights has an influence on the ranking, which highlights the uncertainty in the methodology.

From society perspective this difference is not observed; the results are consistent and favour larger structures (alternatives L and M).

Before drawing conclusions, it is useful to learn more about the robustness of this ranking, which will be treated in the next section.

Table 5.12 Ranking of configurations for each method, obtained from operator perspective.

Ranking	No weights (equal weights)	Weighed (ranking)	Weighed (rating)
1	M	I	I
2	I,L	M	J
3	I,L	J	L
4	J	L	M
5	N	N	N
6	C,D	C	D
7	C,D	D	C
8	F,G	F	F
9	F,G	G	E
10	E	A	A
11	A,H	B	B
12	A,H	E	G
13	B	H	K
14	K	K	H

Table 5.13 Ranking of configurations for each method, obtained from society perspective.

Ranking	No weights (equal weights)	Weighed (ranking)	Weighed (rating)
1	M	L	L
2	I, L	M	M
3	I,L	J	J
4	J	I	I
5	N	N	N
6	C,D	D	D
7	C,D	E	E
8	F,G	F	F
9	F,G	C	C
10	E	G	G
11	H,A	K	K
12	H,A	H	H
13	B	A	A
14	K	B	B

Step III: Analyse sensitivity

Sensitivity analysis provides insight into the robustness of the ranking presented in the previous section. This section demonstrates the results, following the two methods presented in section 4.4.2.2 (step III).

Mathematical sensitivity analysis

Mathematical sensitivity analysis involves varying one parameter while keeping the ratio of others constant. This section presents the results for criteria CAPEX and Operability, displayed in figure 5.10a and 5.10b respectively. This set of results assumes the society preference.

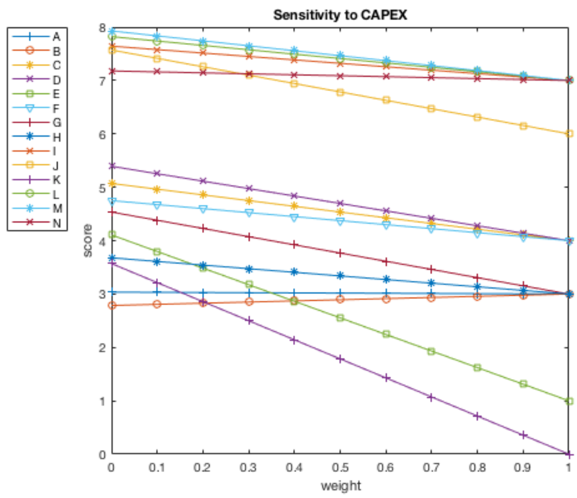
The rank of the alternative can be easily observed: the alternatives are organised such that the highest-ranked alternative equals the highest line for a given weight. The ranking is evaluated for the weights 0 (not important) to 10 (very important). Note that for increasing weight, the rank converges to the score assigned to the criterion that is varied, because ultimately the other criteria are not taken into account any more.

For CAPEX, the ranking does not change much throughout this range. What we can observe, is that alternative J is more sensitive to a change in CAPEX weight with respect to its rivals. Comparing concept J with similar concept I, which is cheaper due to the flexible netting, we can check that this is correct. However, although useful for identifying (in)sensitivities, this figure alone does not provide enough information for the DM to identify the best performing concept.

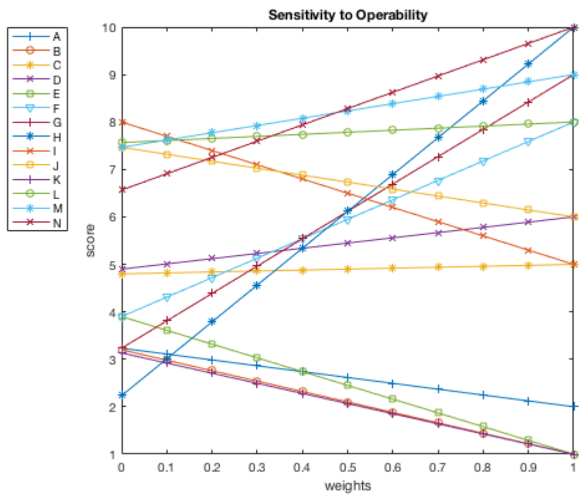
The graph obtained from varying criterion Operability shows more variation. The sensitivity is higher and the graph suggests that larger aquaculture concepts, present in alternatives G, H, M and N are becoming more interesting as the weight of the operability criterion increases. This is no surprise and is a direct result of the assumptions made in the scoring process.

The real challenge is to identify in which range of criterion weights the answers should be sought. In table 5.11, the minimum and maximum weight assigned is 0,02 and 0,3. In this interval, figure 5.10b cannot deliver a conclusive answer. Thus, an estimate of a sensible range of criteria weights is required, and the uncertainty in assigning those weights would need to be studied in more detail. Besides, the assumption that the ratio of all other weights remains equal while varying one parameter helps to simplify the problem, but this ratio also depends fully on the expression of DM preference and is therefore also subject to uncertainty.

To overcome these issues, stochastic sensitivity analysis was conducted and will be presented in next section.



(a) Sensitivity to CAPEX



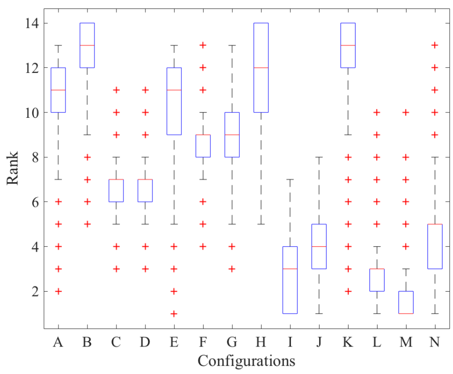
(b) Sensitivity to Operability

Fig. 5.10 Results of mathematical sensitivity analysis for varying CAPEX and Operability weights

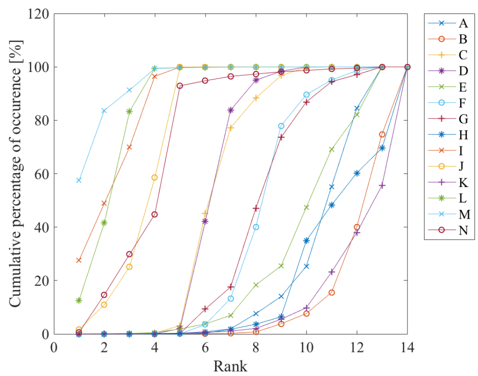
Stochastic sensitivity analysis

This section presents the inputs and results following from the method proposed by Butler et al., followed by the results from Hyde's methodology. The inputs for the sensitivity analysis have been included in appendix D. In this section, the outputs of the Monte-Carlo simulations are given. For each case, 10.000 simulations were executed, which was enough for the solution to converge.

Inspection of figure 5.11, showing results for the method by Butler et al., suggest that configuration M, L and I are the top-3 alternatives. They are the only alternatives scoring first place, with 58%, 27% and 15% occurrence respectively. For most combinations of weights, these alternatives end up in the top-3 and for no combination do they exceed rank 5.



(a) Boxplot of ranking

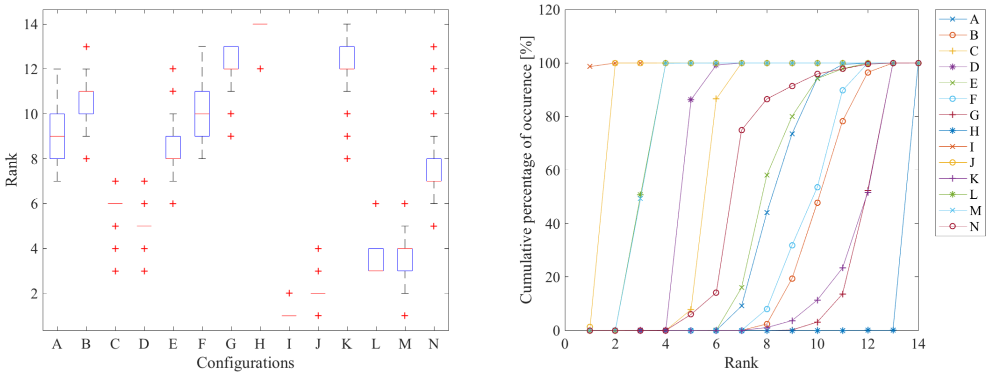


(b) Cumulative ranking

Fig. 5.11 Ranking with randomly sampled weights from uniform distribution according to methodology by Butler et al.

Applying Hyde's methodology allows to study different DM preferences by adjusting the input distributions, which are given in appendix D. The implementation is presented step-wise to demonstrate the impact on results.

Figure 5.12 displays the outcome of Hydes methodology, varying at this stage only the weights and not the score values. In this figure, the preference values of the operator were chosen. This leads to a different order of preference than obtained with Butler's method. While alternatives M and L still score well and are in top-4, two things changed. First, alternative M has shifted to fourth place whereas alternative I became the top-pick, closely followed by alternative J. This resembles closely the ranking obtained in table 5.12. Another difference with Butlers method is that the uncertainty in the final ranking is reduced: the plots suggest a rather decisive order of preference.

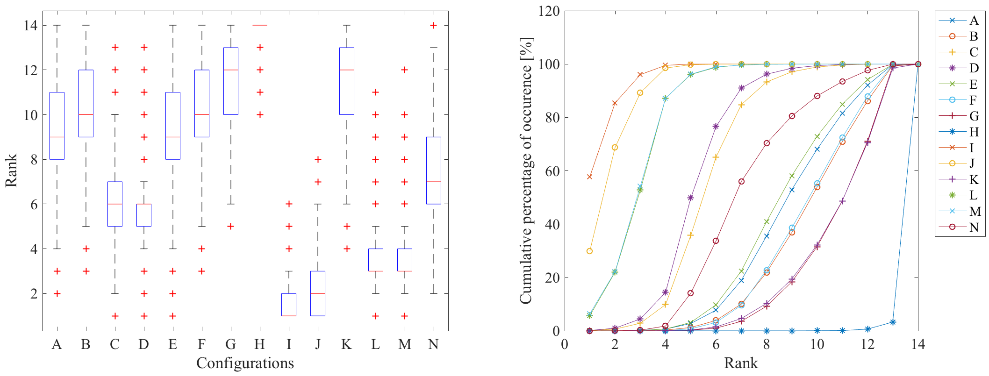


(a) Boxplot of ranking

(b) Cumulative ranking

Fig. 5.12 Ranking based on operator perspective with *randomly sampled weights* according to methodology by Hyde.

To complete the implementation of Hyde's methodology, the uncertainty in scores is taken into account in figure 5.13. As expected, a smoother curve is observed with higher variance of results, providing a more nuanced perspective. Where alternative I scored near 100% first place in previous case, that is now reduced to 58 %. Still, the same sub-set of alternatives constitutes the top-4, but it is more difficult to say which one is the absolute 'best'.

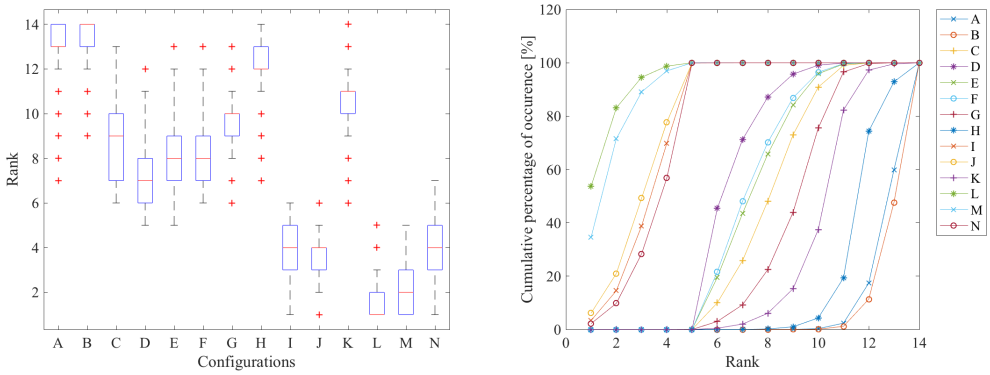


(a) Boxplot of ranking

(b) Cumulative ranking

Fig. 5.13 Ranking based on operator preference with *randomly sampled weights and score values*, according to methodology by Hyde.

In previous two cases, the preference of the operator was chosen. Figure 5.14 demonstrates that adopting the *society* preferences leads to a different decision, favouring alternatives L and M. This result is analogous to the ranking in table 5.13, but the advantage of this stochastic method is that it gives more insight into the robustness of the ranking.



(a) Boxplot of ranking (b) Cumulative ranking

Fig. 5.14 Ranking based on society preference, with *randomly sampled weights and score values*, according to methodology by Hyde.

5.5 Discussion

This section interprets the results of the decision-making framework and their limitations.

5.5.1 Choosing the best concept

First of all, the results point at different preferred options for the *operator* or *society* preference. From the operator perspective, configuration I and J are preferred, which are both based on the Hexicon platform. From society perspective, the more complex configurations L and M are superior (followed by I and J.) Reassuringly, by evaluating the criteria-mapping figures and the outcomes of all stochastic sensitivity analysis methods, it can be concluded that all four concepts consistently end up in the same set of superior alternatives.

Re-evaluating the *society* preference, and considering that all proposed concepts would be improvements to the status quo, it seems most reasonable to proceed with more feasible configurations I and J.

This decision is supported by two necessary adjustments in the assumptions. First, the utility function associated with the technology readiness criterion should be revised. It is felt that the utility of the technological readiness of configurations I and J is underestimated in the current ranking, hence it is expected that they are better that their ranking shows. Second, the assumption of constant rearing density may not be valid because Kumar suggests that smaller cages can have a considerably higher stocking density [39]. While total cage volume in the farm remains equal, this would allow higher salmon production in configurations I and J, which feature smaller cages compared to configurations L and M. These two arguments support the selection of configuration I and J.

Between the configurations I and J, the results of the sensitivity analysis point to alternative I as the ‘most preferred’ option. While opting for configuration I would compromise a little on studying the maximum potential benefits of the MUP, opting for a design based on relatively well-known technologies maximizes the chance of developing useful recommendations about engineering challenges for the nearer future. Moreover, it is expected that the outcome of studying configuration I will also largely apply to configurations J,L and M.

5.5.2 Limitations

It should be acknowledged that the accuracy of identification of criteria, measurement of performance and scoring of alternatives can to a large extent be improved. Even though professionals in relevant fields have contributed with their expertise, the evaluation remains subjective and based on rough and intuitive estimates. It is expected that involvement of a wider range of relevant experts could greatly improve the inputs to the MCDA framework.

Although it is believed that the framework is effective in reaching its objectives, it also has limitations. First, the validity of the aggregation of weights into a single-synthesizing criterion is a matter of concern and widely addressed in MCDA literature. To compensate for this uncertainty, mapping the scores to the criteria space and using a reference-ranking without weights were seen as helpful tools.

Moreover, the 'rightness' of the decision outcome cannot be predicted beforehand, especially not in such early stage. Although there are many claims that MCDA has led to succesful decision-making in a wide range of applications and real-world problems , there were very few *ex-post* analysis studies found to confirm those claims.

Furthermore, it is unclear to what extent heuristics play a role in this decision-making process. Representativeness heuristics are known to play a role in MCDA analysis [14] (p.41). Opting for the familiar Hexicon platform could potentially be the result of similarity-bias, when concepts similar to an already known platform are scored higher than others without a solid basis. Lastly, it is important to evaluate and be aware of hind-sight bias while making the final decision. Opting for the Hexicon platform may appear logical and evident all along, but a series of notes made at the start of this project confirms there was no basis to make such judgement.

Lastly, the design procedure failed to take into account, with adequate measures, fish welfare and the moral relationship between humans and the aquatic world. Starting at the conceptual design stage, the design process should incorporate major issues such as, but not limited to: the health of the farmed fish, interaction with wild fish stocks and spreading of disease. Adopting the Value Sensitive Design framework, developed at Delft University of Technology, may be an effective way to do this.

Chapter 6

Preliminary Design Analysis

This chapter analyses in more detail the preferred concept which was selected in Chapter 5. First, section 6.1 presents a design update of the platform and farm, followed by a review of the configuration selection in section 6.2. Section 6.3 highlights the findings from the comparison between the multi-use concept and stand-alone platforms, resulting in a list of threats and opportunities regarding the further development of MUPs presented in section 6.4.

6.1 Conceptual design update of the platform and farm

In light of new information obtained from Hexicon related to the development of the multi-turbine platform, which was received after the conceptual design stage, a design update of the preferred multi-use concept was carried out. The update is presented in this section.

6.1.1 Update of the wind energy module

The original conceptual design was based on the first generation platform developed by Hexicon, the Dounreay Trì platform. During the end-phase of the conceptual design stage, this concept was updated by Hexicon to the second generation design portrayed in figure 6.1. The 2nd generation features several engineering improvements, most notably the inclined towers. This allows a large reduction of platform size which leads to lower platform costs. The new platform is therefore used as basis for the updated MUP.

The main dimensions of the updated platform are the spacing between the hubs of the wind turbines (187 m), platform length (135 m) and platform beam (65 m). Additional details about platform dimensioning are provided in Appendix H.

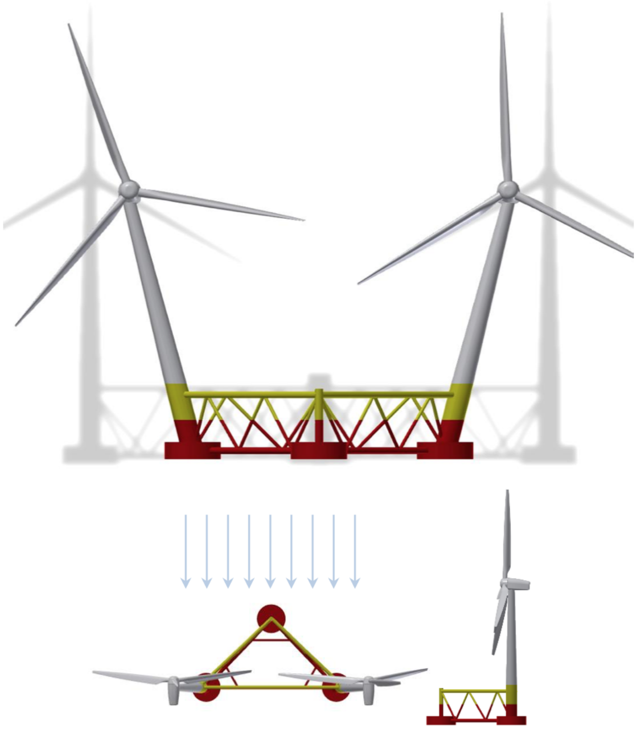


Fig. 6.1 Illustration of the 2nd generation Hexicon platform. The 1st generation platform size is displayed in grey for comparison. (Courtesy: Hexicon AB.)

6.1.2 Update of the aquaculture module

6.1.2.1 Sizing

Because the updated wind energy platform is smaller, the volume of the aquaculture module has reduced considerably with respect to the conceptual design stage. Furthermore, the cage depth has been adjusted to 15 meters so that it equals the draft of the platform. This was done to eliminate concerns related to deformation of the cage underneath the platform. According to Jensen, the depth of modern salmon cages ranges between 15 and 48 meters [32]. Hence, the new depth is at the low end of this range and could be increased if deformation at this depth is not an issue.

The volume change which results from these two measures is indicated in table 6.1. How the reduction of the cage volume affects salmon production will be evaluated in section 6.1.4.

Table 6.1 Aquaculture module dimensions

	Updated design	Original design	Units
Diameter	54	80	m
Depth	15	30	m
Volume	32.500	163.600	m^3

6.1.2.2 Specification of major components

This section specifies the material of the collar and type of weight system for the cage module, which have not been specified thus far. The collars are made from high-density polyethylene (HDPE) because they are cheap, lightweight, offer good floatation and are suited for exposed environments [39]. Besides, to maintain net shape while exposed to currents and waves, a sinker tube is chosen instead of conventional discrete weights because the first is considered more suitable for offshore conditions [11, 41, 59].

6.1.2.3 Review of the cage type

One concern which needs attention before fixing the concept configuration is uncertainty about the suitability of the net-pen cage for offshore environments. While small cages are more suitable for exposed environments than large cages, according to Kumar [39], it is not evident whether traditional net-pen systems can operate in exposed environments in the first place, and if so, what the maximum dimensions of the cage would be. Because this issue may be very critical to the further development of this concept it is considered useful to re-evaluate at this stage the suitability of various cage designs in exposed conditions. For this purpose, the three most common designs of coastal fish cages are considered and presented in figure 6.2.

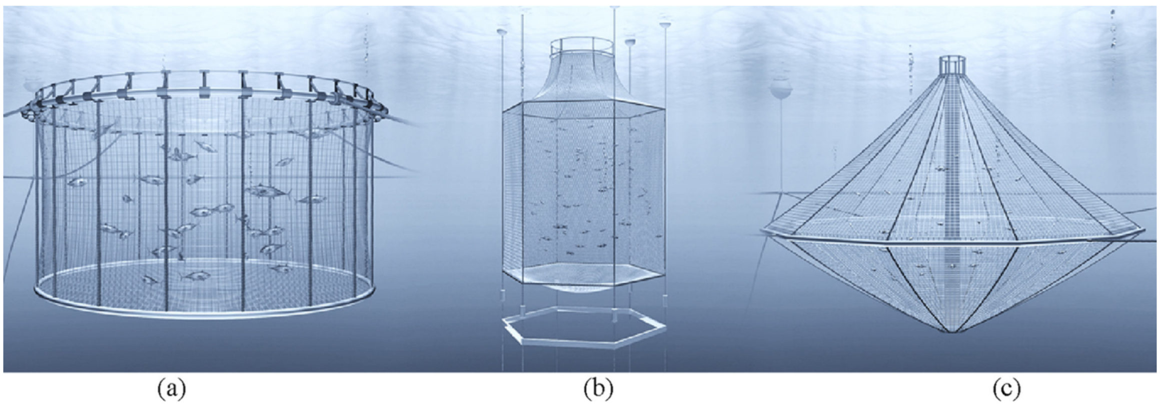


Fig. 6.2 Different fish cage designs (a) Gravity-type flexible cage (b) Tension-leg system (c) Rigid frame fish cage [15]

Two main considerations are defined which govern the choice of aquaculture module type in a MUP:

1. It should withstand exposed conditions
2. It should be compatible with the wind energy module

In this section, the cage types will be shortly evaluated in light of these considerations. Note that the response to environmental loading largely influences the compatibility with the semi-submersible wind energy platform.

Studying the first consideration reveals that the cage types have a different way of coping with environmental loading, illustrated in figure 6.3. When exposed to high currents, which dominate the environmental loading [41, 59], the net-pen shape deforms but it remains floating. The response of the tension-leg system is to submerge and the rigid-frame system is always submerged.

The net-pen system seems most compatible with the wind energy platform because it is self-buoyant and can be easily deployed within a multi-use platform, without requiring

(a) Traditional net-pen cage *(Courtesy: SINTEF)*　(b) TLP *(Courtesy: [29])*　(c) Ocean Spar *(Courtesy: Ocean Spar Technologies)*

Fig. 6.3 Methods of coping with environmental loading for the three fish cage designs

additional mooring installations. However, one concern is that the deformation of the netting may lead to rubbing against the wind energy module, which increases the risk of damage to the netting and ultimately fish escape. During the design, this problem needs to be resolved, either by reducing the cage diameter or by finding alternative ways to minimize deformation, of which the latter will increase the load on the bridle lines and moorings.

The tension-leg system may present issues with the coupling to the wind energy platform. In contrast to the semi-submersible wind energy module, tension-leg mooring systems do not permit horizontal wobbling when exposed to waves, which is likely to cause repeated motion-induced stresses. The stand-alone tension-leg system reduces loads on the system by submerging, which includes a horizontal displacement that is restricted by the coupling to the wind energy module in a MUP configuration. The tension leg platform (TLP) is more difficult to install, therefore it is considered more likely that a tension-leg system would be compatible with a tension-leg wind energy support structure.

Although the fixed net-volume is a distinct advantage of the rigid frame cage, the submersible does not seem suited for coupling to a floating semi-submersible. In addition, the cage volume of this type is generally much smaller than that of a traditional net-pen system and carrying out husbandry tasks and maintenance requires specialised divers, which brings additional safety concerns.

Although final selection of a suitable cage type depends on the site conditions, it seems that for a modular multi-use design the traditional net-pen has most potential. Hence, the decision is made to stick to this concept. It should be stated explicitly that this choice is governed by the compatibility with the wind energy module, and does not suggest that the same choice applies for the stand-alone activities.

6.1.3 Overview of updated MUP design

Figure 6.4 illustrates the updated configuration of the modular MUP platform.

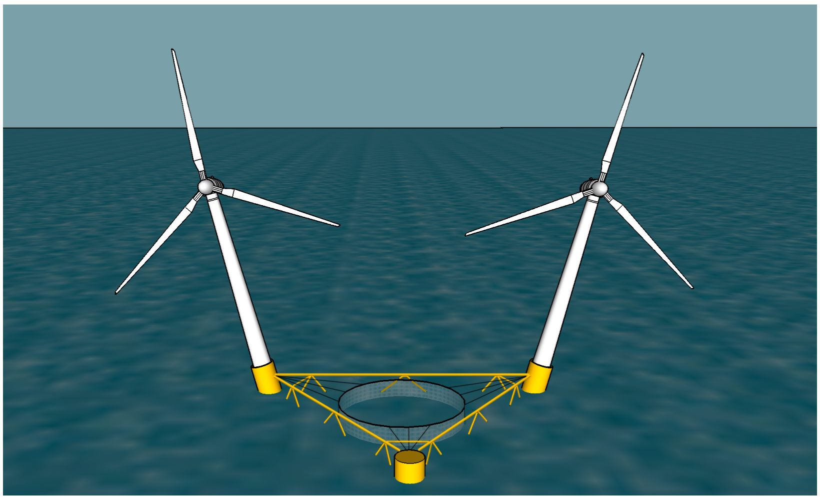


Fig. 6.4 Illustration of the final conceptual design, featuring an updated Hexicon platform and traditional net-pen cage. The floating collar and connecting bridle lines are lifted above sea level for illustration purposes.

6.1.4 Update of the farm

The update of the conceptual platform design in the previous section does not change the installed wind power capacity in the wind farm, but does reduce the total available cage volume in the farm. The adjustments to the wind energy platform and the revision of cage depth have large consequences for the maximum available cage volume, which is reduced by almost 80% compared to the first design.

In chapter 4 and chapter 5, it was considered important to keep the total salmon production constant at 10.000t to allow fair comparison of the alternatives. Therefore, several platforms did not feature an aquaculture module and the space in the farm was not utilised to its full potential. In this chapter, the 10.000t production is not seen as a strict requirement and a farm is considered where each platform features an aquaculture module, which leads to the maximum possible aquaculture output for this configuration, given in table 6.2.

Considering that the cage volume has reduced from 1.778.000 m^3 to 1.380.000 m^3 the updated production capacity would amount to 7.760t per annum, again assuming proportional scaling of production volume with volume of the cage. The validity of this assumption is not certain given Kumar's remark that smaller cage volumes allow higher stocking densities, and would thus deliver higher yields [39]. Further research or input from the aquaculture industry is required to clarify this point, but for now a basic estimate suffices.

An advantage of the modular MUP is that the scale of either wind energy or salmon production can easily be modified to fit project-specific requirements, by adding or removing aquaculture modules. However, what is learnt from scaling to farm level, is that the wind energy power capacity limits this flexibility because the net-pen cannot be installed without the platform, but the platform can be installed without the net-pen. Effectively, this means that large salmon farms based on this concept do not go together with small wind farms.

For illustration purpose, a typical farm lay-out consisting of 10 platforms is given in figure 6.5.

Table 6.2 Update of farm parameters

	Value	Units
Wind farm		
Installed capacity	800	MW
Turbine rated power	10	MW
Number of platforms	40	
Salmon farm		
Yearly production capacity	7.760	t
Number of cages	40	
Cage volume	34.500	m^3
Total cage volume	1.380.000	m^3

Fig. 6.5 Illustration of a typical wind farm lay-out with distributed platforms (Courtesy: Hexicon. Image is based on the first generation stand-alone Hexicon concept)

6.2 Review of concept selection in view of design updates

This section discusses whether to opt for the updated design or for the original concept, ultimately favouring the updated design.

The disadvantage of the updated design is the reduced cage volume, which has large consequences for the maximum salmon production output. The advantage of the updated design is the lower CAPEX due to the smaller platform compared to the original design. This suggests that the sizing of the two units can be optimized. Being aware that optimization is possible in a multi-use configurations is relevant, because while comparing the multi-use platforms against the stand-alone platforms, it is assumed here that they are of the same size.

When viewed on platform-level, the question which design is better requires a rough estimate of which dimensions are favourable. However, this is difficult to obtain and requires bold assumptions. The choice is made relatively easy by comparing the multi-use concept against its single-use reference.
This comparison introduces a strong argument which favours the selection of the updated platform, which is as follows. The best stand-alone concept should be compared to the best multi-use concept, which was stressed in section 3.1.1. Therefore, the updated Hexicon platform would become the reference concept on the wind energy side. If the original Hexicon design would then be chosen as basis for the MUP, the reference stand-alone wind energy concept would outperform the 'outdated' MUP concept from the start, at least from wind energy perspective. It is then assumed that the cage volume reduction is acceptable.

Finalizing the decision to opt for the updated platform requires a quick reflection on its performance compared to the alternative concepts addressed in the conceptual design stage. It was decided not to fully re-evaluate the configuration selection and to proceed with the updated design, supported by the following two considerations.

First, because choosing an appropriate cage depth was uncertain in the first conceptual design sizing estimates, the depth of all the concepts (except concept 5[1]) was set equal at 30m. Because the volume of the high-ranked cages scales linearly with depth, the reduction in depth during the update of the platform is not likely to lead to changes in the configuration selection outcome.

Second, the reduction in platform size decreases the CAPEX related to the preferred concept, which to a lesser extent is possible for other platforms. Because CAPEX was assigned large weight in the decision process, it is expected that the updated MUP would remain the top-pick.

6.3 Preliminary design evaluation

6.3.1 Approach

This section is dedicated to a preliminary evaluation of the updated conceptual design, where it is aimed at learning more about the performance of the MUP compared to stand-alone single-use references. The expected result is a list of threats and opportunities related to the design and O&M of the multi-use farm.

The performance of a wind farm or salmon production farm can be evaluated by assessing the trade-off between performance along two objectives: maximizing energy or salmon yield while minimizing costs. Many decisions in the development of a farm, for instance in the design, site selection or O&M strategy, are based on this trade-off.

The performance on these objectives is influenced by various types of requirements related to the functioning of the platform during its servicelife (e.g. the ability to stay on the same place) and to activities during the lifecycle (e.g. during development, installation, operation, maintenance and decommissioning). From a technical viewpoint, it has been attempted

[1]Because concept 5 did not score well overall, it was not considered a potential candidate for preliminary design analysis.

to list those requirements which offer an opportunity or may pose a threat to the further development of the multi-use concept.

In this regard, Celluci distinguishes between operational and technical requirements, also called the “problem space" and “solution space" respectively [12, p. 10]. By identifying similar requirements in the "problem space", joint solutions are sought in the "solution space". By observing changes or overlap in the materialisation of solutions into system components and processes for the stand-alone and multi-use platform, it is expected that threats and opportunities can be discovered.

Some of these solutions translate into hardware solutions, of which examples are given in table 6.3. Analysing the overlap in hardware solutions is expected to lead to suggestions for cost-reduction opportunities. It was decided to focus on costs-saving opportunities instead of profitability because analysing the latter requires an estimate of total costs and of the revenues, which would introduce large uncertainties.

Table 6.3 Examples of requirements and corresponding hardware solutions.

Higher-level requirement	Lower-level requirement	Hardware solution
Accommodate activities	Stay on the same position Stay afloat	Mooring Semi-submersible platform / floating collar
Maintenance	Transport of crew	Workboats / crew transfer vessel

In the remainder of this section, the requirements are lumped into the term ‘evaluation items’. Table 6.4 lists them for easy reference and denotes whether they apply to the aquaculture component or wind energy component of the MUP. It is useful to explicitly state that for the single-use activities, the list of evaluation items could be more extensive. This section almost exclusively lists those challenges which arise by combining the two modules. An exception is made when a challenge poses a threat to the feasibility of the whole concept, such as the ultimate environmental conditions in which a traditional net-pen can operate.

The evaluation items are analysed consecutively in the next section (6.3.2). Because of their similarity and the large overlap between wind energy and aquaculture, the items Operations and Maintenance are treated simultaneously in section 6.3.2.9.

Table 6.4 List of main objectives and items for evaluation. Checkmarks indicate that the item is relevant to single-use aquaculture and/or single-use wind energy.

	Aquaculture	Wind Energy	Direction
Objectives			
Salmon yield	✓		maximise
Energy Yield		✓	maximise
Costs	✓	✓	minimise
Evaluation items			
Development			
Certification			
Site survey			
Site selection			
Functional requirements			
Station-keeping			
Structural integrity of the platform			
Structural integrity and deformation of the cage			
Ensure good fish growth conditions			
Installation, Operation and Maintenance			
Installation			
Maintenance			
Operations			

6.3.2 Analysis & findings

6.3.2.1 Certification

Because offshore aquaculture and floating wind energy are largely uncharted territory, investors and operators face challenges related to risk, safety and compliance. Certification by a third party helps to manage those risks and concerns by checking compliance of design and components to internationally recognised codes and standards, aiming to provide investors and operators with confidence that the project will be successful during its intended service life.

In this regard, the first observation is that the design lifetime of the modules is different. While the design life-time of a semi-submersible wind energy platform is typically around 20 years, traditional net-pen cages have a lifetime of 7-10 years [26, 61]. After that, the net-pens are replaced. This is relevant because the expected life-time has an effect on the design load cases which need to be considered during the design and certification. Because the aquaculture net-pen has a shorter lifetime, the design driving load cases will likely be less conservative than for the wind energy platform.

Related to the previous point is the design method which is used. Offshore wind energy structures comply to strict offshore guidelines, similar to the oil and gas industry, and design procedures involve studying limit states with carefully selected load-cases, based on for instance 50-year return periods. Common subjects of study are Ultimate Limit State (ULS) and Fatigue Limit State (FLS). In aquaculture, such ultimate limit state design methods have not been (fully) adopted, although Kristianssen indicates that this design method is gaining interest [38]. This suggests knowledge transfer is possible where offshore wind energy could benefit offshore aquaculture.

Opportunity for aquaculture: learn from limit state design methods used in offshore wind energy

6.3.2.2 Site survey

One of the requirements for the design and certification is a detailed description of environmental conditions at the site. To study the load cases for ULS or FLS, detailed measurements related to e.g. bathymetry and wind,wave and current conditions are required which are obtained during a site survey.
Because both wind energy and aquaculture have a clear need for this data, and in a multi-use project inherently operate at the same site, both parties could benefit by sharing environmental data obtained through a survey of the multi-use site.

Opportunity: share (costs of) site survey data

6.3.2.3 Site selection

Selecting an appropriate site is an important aspect in the development phase of a wind farm or aquaculture farm, both economically and technically. In a multi-use concept, site selection of MUPs would be conducted with additional constraints with respect to the stand-alone activities.

It is likely that an optimal site for wind energy is sub-optimal for aquaculture, and vice-versa. Whereas wind energy is mostly concerned with having high wind speeds, these often induce higher currents and waves which aquaculture seeks to avoid. Aquaculture seeks sites with good growth conditions, focusing on for wind energy irrelevant parameters such as water temperature and salinity. It can be deduced, according to equation 6.1 that the probability of having a certain availability of sites fulfilling the combined set of criteria is smaller than the probability of having the same availability with a smaller number of criteria.

$$P(A_{sites}|w,t,s) < P(A_{sites}|w) \tag{6.1}$$

where $P(A_{sites})$ is the probability of having a certain availability of sites, under the conditions that w (wind), t (temperature), s (salinity) are in a certain range.

Site selection has a large impact on salmon yield, energy yield and costs. Hence, the availability of suitable sites determines to a large extent the feasibility of MUPs in the future.

Threat: non-availability of (enough) sites with optimal conditions for both activities

6.3.2.4 Station keeping

Station keeping means that the structure can stay on one place, which is ensured by the mooring system. Both floating wind energy structures and aquaculture cages require anchoring to the sea-bed, which leads to several opportunities and threats.

The first opportunity related to station keeping was suggested by Fredheim, who pointed out that knowledge transfer is desired because aquaculture does not have experience with mooring systems in exposed environments [19].

The second opportunity of a multi-use system compared to the stand-alone modules, is that one mooring system can be used instead of two. This could reduce the mooring material costs and mooring installation costs.

It is likely that strengthening of the single-use wind energy mooring will be required when the platform is converted into a MUP, for two reasons. First, the hydrodynamic drag on the cage structure is added to the total load. Second, the presence of fish farming increases the rate at which bio-fouling occurs on the hull. If untreated, this increases the hydrodynamic drag on the MUP structure with respect to the stand-alone wind energy platform. This suggests that either a higher bio-fouling multiplication factor should be used to calculate the drag on the hull, which in turn prescribes redesign of the mooring, or routine-based cleaning of the hull should be performed. Both measures would lead to additional costs.

Hence, the potential mooring material costs savings will be (partially) negated by the redesign of the multi-use mooring and/or bio-fouling removal.

Opportunities and threats:

1. *Opportunity: knowledge transfer from wind energy to aquaculture, regarding mooring design*

2. *Opportunity: cost-reduction on the mooring material and installation costs*

3. *Threat: strengthening of moorings is required with respect to stand-alone platform*

4. *Threat: strengthening the mooring and/or biofouling removal will induce extra costs.*

6.3.2.5 Structural integrity of the platform

The addition of the aquaculture net-pen system to the platform requires an evaluation of how this affects the structural integrity. Because the wind-energy module is designed for exposed conditions and the hull is much larger and heavier than the flexible cage structure, it is not expected to pose significant threats to the structural integrity of the semi-submersible platform[2].

However, it should be checked whether the presence of the fish cage affects the natural frequency of the platform and if the netting structure affects hydrodynamic damping. To test this, numerical modelling or experimental bassin tests can be executed during more advanced stages of the design.

Threat: hydrodynamic response of the cage and platform

6.3.2.6 Suitability of the net-pen cage in exposed conditions

In section 6.1.2.3, the concern was expressed whether the proposed design can function in an exposed environment. It is repeated here for completeness. If the type of cage is not suitable for the conditions in which it operates, loading on the cage system can lead to mortality, reduced fish health and increased risk of fish escape.

Threat MUP: the suitability of traditional net-pens in exposed environments.

6.3.2.7 Ensure good fish growth conditions

Good health is a prerequisite for salmon growth. This section aims to identify differences in the living conditions between the MUP and the stand-alone platforms, which may lead to differences in salmon yield. In open cage systems, some parameters are constant, irrespective of the cage design, such as water temperature and salinity. Here, it was attempted to find those parameters which are affected by the MUP design because they may lead to threats or opportunities.

[2]This expectation is based on personal communication with Niklas Hummel who is responsible for the engineering design of the Hexicon platform

The first potential advantage of the MUP concept is that the large hull of the wind energy module could offer some shelter to the fish. [3] According to Remen, current speed and wave action can cause stress in the fish because they need to "swim faster and spend more energy to avoid contact with the net enclosure and other fishes" [52]. Hence, sheltering structure could reduce their efforts to battle the current and alleviate stress, which contributes to their growth.

On the other hand, because the current ensures water exchange and feed dispersion within the cage, which are critical parameters for good growth conditions, it should be checked that the oxygen flow throughout the cage remains sufficient [41].

Besides, a potential drawback is the heave, roll and pitch motion of the wind energy platform with respect to the coupled net-pen, which may compromise the health of the fish. Agustsson remarks that the relative movement of the cage with respect to the fish inside should be minimized in order to ensure good health [2, p.13].

Opportunities and threats:

1. *Opportunity: sheltering effect may alleviate fish stress compared to stand-alone concept.*
2. *Threat: sheltering effect may reduce oxygen and feed dispersion*
3. *Threat: heave-and pitch motion of the platform may lead to stress*

6.3.2.8 Installation

This section identifies a cost-reduction opportunity for a joint installation strategy.

In case the wind energy platform and aquaculture net-pens were installed separately, or in a share-space configuration, two mooring systems would need to be installed. For the multi-use concept proposed here, only one mooring system is required to hold both the wind energy platform and net-pen in place. Because this mooring would be installed anyway, only one vessel needs to be chartered and the additional vessel which would otherwise be required for the aquaculture mooring installation is not necessary.

[3] This idea originates from a lecture given by Prof. dr. Han Lindeboom from Wageningen University about environmental aspects in offshore wind farm design, during which the sheltering effect of monopile support structures was discussed.

On the other hand, by comparing the multi-use design with the stand-alone design, it should be noted that their configuration is different as net-pens are usually grouped and connected in series of 6 or 8 nets. This requires fewer moorings, which partially negates the cost-sharing potential.

Opportunity: Cost-reduction through joint installation strategy

6.3.2.9 Operation & Maintenance

This section aims to identify opportunities and threats regarding O&M of multi-use farms. Maintenance dominates the costs and activities in wind energy, whereas operation plays a minor role in costs. The opposite is true for coastal aquaculture, in which operations (e.g. feeding, grading, sorting, monitoring, de-lousing) dominate the costs and where maintenance plays a minor role. However, the importance of adequate maintenance strategies for aquaculture can be expected to grow in a future scenario where more automated feeding, handling and monitoring machinery is used at locations further from shore.

Effect of the wind energy module on the operation of aquaculture
On the aquaculture side, performing husbandry tasks when required is critical for growth of the fish [40, 53]. According to Bjelland, operability mainly entails finding the right weather windows [6], that is: having enough weather windows is crucial for the timely execution of time-critical husbandry tasks such as feeding and inspection of the cages. By comparing the multi-use design against single-use net-pens, two opportunities were identified which could enable more weather windows:

- First, the stable wind energy platform may offer a stable boat-landing facility for well-boats, feed-supply vessels, bulk carriers or specialised delousing or cleaning vessels, which according to Kristiansen contributes to more weather windows [38]. In stand-alone aquaculture in sheltered areas, the boats can be moored against the floating collar, but in offshore conditions a traditional net-pen system may not be able to serve as boat-landing structure.

- The second, the stable wind energy module could enable routine husbandry tasks for aquaculture in a wider range of conditions. The downside of stand-alone traditional net-pens is that the floating collar, from which the crew normally operates, is likely not stable enough to ensure safe operation in exposed conditions. This problem may be circumvented in multi-use platforms.

On the other hand, operability is threatened by the larger distance between the distributed platforms in a wind farm, illustrated in figure 6.5. The distributed platforms will reduce the ease of operation for the salmon farmer compared to the stand-alone traditional net-pen farms, which feature groups of cages positioned close together. The level of automation in feeding systems and other routine husbandry tasks will determine to a large extent whether this is a minor or major concern [40].

Effect of the aquaculture module on maintenance of wind energy

On the wind energy side, maintenance is crucial for ensuring a high availability and obtaining high energy yields. A potential disadvantage related to maintenance, caused by the introduction of the aquaculture module, is that a promising maintenance strategy for floating wind energy will no longer be possible. This strategy is related to major preventive maintenance (PM) and corrective maintenance (CM) and aims to tow the structure to shore for major repairs, instead of doing it on-site. This would eliminate the very high charter costs of lifting vessels, and thereby contributes to lowering the overall maintenance costs. The introduction of the aquaculture module blocks this alternative strategy, and requires maintenance to be performed on site, which may lead to additional costs [4]

Cost reduction opportunities through joint O&M strategies

It is thought that shared operations and maintenance strategy could lead to cost reductions related to transportation of crew to and inside the farm. Schöntag categorises possibilities for lowering the O&M costs of a wind farm (see figure 6.6) and identifies transportation as a segment for cost reduction. It is likely that the other segments (staff, equipment, stock, facility) are used only for wind energy specific activities, and therefore do not offer potential for synergies. Transport, on the other hand, is also an evident requirement for operation of the salmon farm and could therefore offer opportunity for cost-reduction in a multi-use farm. This opportunity is confirmed by Wever et al. who report the potential sharing of "vessel fixed costs" in multi-use farms as outcome of stakeholder meetings with the aquaculture industry [68].

[4]Note that this only applies to floating wind energy structures, because bottom-founded wind energy structures (such as the jacket proposed by He in figure 1.2d) do not offer this possibility.

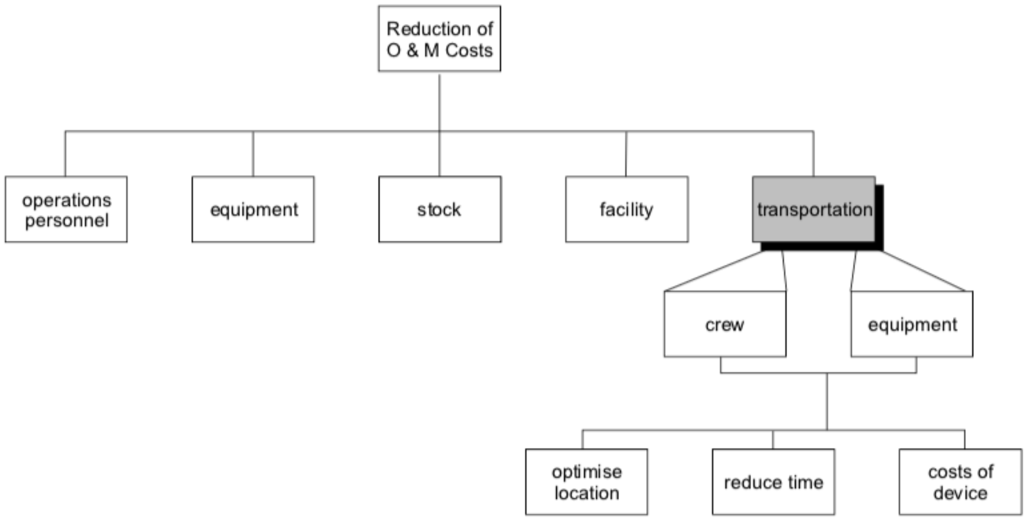


Fig. 6.6 Segmentation of O&M costs for offshore wind farms [57]

Opportunities and Threats:

1. *Opportunity: Boat-landing facility allows more weather windows*
2. *Opportunity: Wind energy platform may serve as stable base to operate from*
3. *Threat: Distributed production complicates operations such as sorting and grading of fish*
4. *Opportunity: Cost-reduction through shared use of O&M vessels*
5. *Threat: Inhibiting the tow-to-shore major repair strategy for major O&M tasks*

6.4 Overview of threats and opportunities

An overview of the threats and opportunities outlined in the previous section is given in table 6.5. The second column aims to indicate whether the expected opportunity or threat is low (+ / -), average (++ / - -) or high (+++ / - - -).

Table 6.5 Identified opportunities and threats in relation to the main objectives

	Magnitude	Objective
Opportunities		
Learn from limit state design methods	+	Engineering
Cost-reduction through site survey data gathering	+	Costs
Knowledge transfer	+	Engineering
Mooring material and installation cost reduction	+ +	Costs
Sheltering effect may alleviate fish stress	+	Salmon Yield
More suitable weather windows due to boat landing facility	+	Salmon Yield
More suitable weather windows due to stable platform	+	Salmon Yield
Cost-reduction opportunity of O&M vessel charter	+++	Costs
Cost-reduction through joint installation strategy	+	Costs
Threats		
Traditional net-pen not suited for exposed environments	- - -	Engineering, Costs
Non-availability of optimal site conditions for both activities	- - -	Energy Yield, Salmon Yield
Moorings need to be strengthened	-	Engineering, Costs
Hydrodynamic response of the coupled cage and platform	-	Engineering
Sheltering effect may reduce oxygen and feed dispersion	-	Salmon Yield
Heave, roll and pitch motion may leed to stress for the fish	-	Salmon Yield
Tow-to-shore strategy may be compromised w.r.t. stand-alone wind energy	- -	Costs
Availability of wind turbines should not be reduced by aquaculture operations	- - -	Energy Yield

Chapter 7

Key focus areas

7.1 Selecting key focus areas

7.1.1 Approach

Previous section provided a list of threats and opportunities which can not all be evaluated in detail during this project. Prioritization is required to be able to achieve more detailed insights in these topics, for which the main consideration is the impact new insights can have on the expected feasibility of the multi-use concept, either from technical or cost perspective.

From technical point of view, priority is given to those aspects which are most pressing for the technical development of multi-use design.

From cost-reduction perspective, segmenting the total expenditure into its component parts should help to prioritize efforts and allow to focus on opportunities and threats which can have the largest impact. Therefore, the cost-related items listed in table 7.9 are evaluated against the cost breakdowns which are presented in the next section.

7.1.2 Prioritizing cost-related opportunities and threats

This section provides pie-charts outlining the share of cost components in the total expenditure of wind energy and net-pen salmon aquaculture. The cost components and shares within traditional salmon aquaculture net-pen systems were adapted from data by Liu et al. [43] and presented in figure 7.1. The data was compared to production cost data reported by Marine Harvest [40] and is considered representative. The components and shares of total cost from the wind energy side were obtained from Hexicon and are based on a first estimate considering one specific case. Hence, the reader should be aware of the uncertainty regarding these numbers, which are presented in figure 7.2.

Four remarks should be made about the presented charts:

- First, it should be noted that the pie-charts give only an indication of the share of each cost component, and do not take into account time value of money and cash flows.

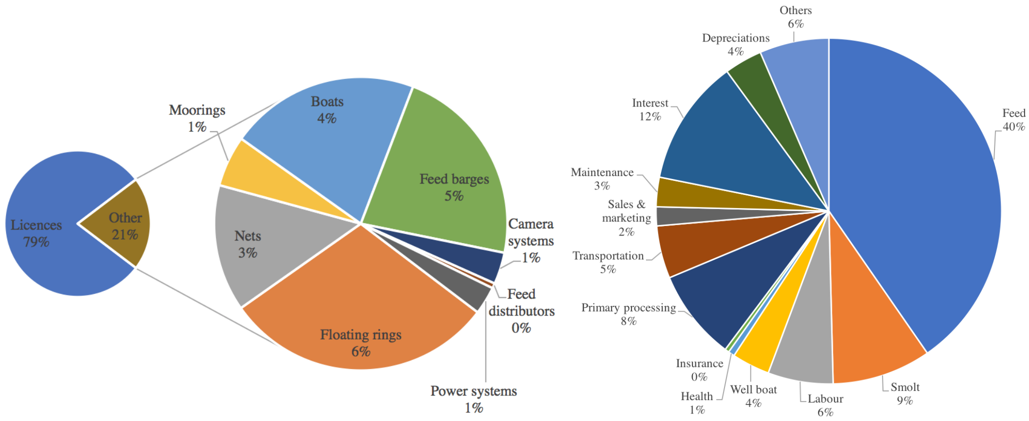
- Second, in figure 7.1, the share of the moorings, nets and floating rings is underestimated. Replacement, which is required every 5 years, has not been taken into account.[1]

- Third, on the aquaculture side, an important consideration is that production costs are expected to increase if production moves to exposed areas, regardless of the farming method [36, 40]. This will be driven by technical challenges and more complicated logistics, leading to cost increases for workboats, moorings, cages and personnel, while other costs such as the cost of feed or smolt are not influenced by this factor. Because the values presented in this section are based on today's practices, they will not reflect the cost distribution in the future. The expected cost increase makes sharing infrastructure more attractive than when this is compared to the costs incurred today.

- Fourth, in figure 7.2b the overhead costs make up a large part of OPEX and consist largely of costs related to grid connection and power delivery, which were not segmented.

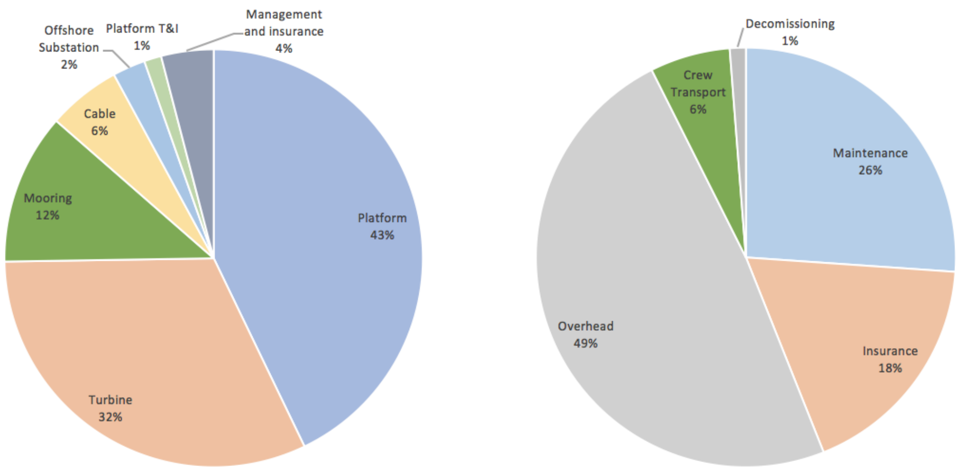
By evaluating the size of the segments in the pie-chart which are eligible for cost-reduction, it can already be seen that for aquaculture, relatively small cost-reductions can be made, primarily in CAPEX, while the production costs in this industry are much more sensitive to OPEX [36]. Regarding wind energy, in a similar manner, it is observed that small cost-reductions can be made primarily in OPEX, through sharing of vessels, although the LCOE is most sensitive to changes in CAPEX [60]. This already limits the expectation for total cost-saving opportunities in relation to overall expenditure.

[1] Appendix G provides the input data for this figure



(a) Capital expenditure (b) Operating expenditure

Fig. 7.1 Cost distribution within CAPEX and OPEX for a 3.300 MT Atlantic Salmon farm case study (Created based on data by Liu [43]. Note: the capital expenditure does not take into account replacement of parts)



(a) Capital expense (b) Operating expense

Fig. 7.2 Cost distribution within CAPEX and OPEX for a 560 MW Hexicon case study

7.1.3 Choosing key focus areas

From technical perspective, the suitability of net-pen cage systems in exposed environments is considered most pressing. Besides, mooring design for fixed and flexible structures will be evaluated, which is expected to also give insight into costs of these moorings.

From cost perspective, inspection of the cost segmentations of wind energy and aquaculture confirms that a cost-saving opportunity exists in the moorings and transportation infrastructure. Because these costs are also expected to increase, it is interesting to investigate those in more detail. On the other hand, the expected cost-reduction for gathering environmental data about the site is minimal, and is not evaluated in more detail.

To study the opportunities and threats related to salmon yield and energy yield is important, but requires the use of more sophisticated models and expertise, which are not readily available at this time.

This leads to four focus areas, with the following objectives:

1. To study the suitability of the MUP concept for exposed sites, by providing insight into the extreme operating conditions of traditional net-pen systems.
2. To estimate the need for strengthening the mooring in a MUP and deduce from that the cost-sharing potential, by estimating and comparing the loads on the mooring systems of the stand-alone platforms.
3. To estimate the sharing potential for vessel costs during O&M activities, by identifying opportunities and estimating vessel costs in different scenario's.
4. To assess whether eliminating the tow-to-shore maintenance strategy can be a show-stopper for MUPs, by estimating and comparing the costs of the strategy against a baseline strategy.

The following sections are dedicated to these four focus areas.

7.2 Focus area 1: Suitability of net-pen systems for exposed conditions

7.2.1 Approach

This section aims to present insight into the extreme operating conditions of traditional net-pen systems, which in turn helps to evaluate the suitability of the MUP concept at exposed sites. If the flexible netting appears not to be suited for (a range of) exposed environments, an alternative concept may be preferred for further development of MUPs, for example those based on a rigid netting structure.

Extensive modelling is required to both calculate the loading and study deformation of traditional net-pen cages in exposed environments, which has only recently received attention [40]. During a first literature review, several studies on loading and deformation of net-pens in sheltered sites were found, but the operational limits were not treated. Later during the project, Shen et al. published a paper discussing these operational limits of net-pen systems[59], which has been useful for evaluating the feasibility of the aquaculture module in the multi-use concept. The next section is largely based on his findings and discusses their implications to the further development of MUPs.

7.2.2 Analysis and findings

7.2.2.1 Defining survival conditions

To evaluate to what extent traditional net-pen systems can operate in exposed areas, proper criteria should be chosen to define survival conditions. Shen proposes the following:

- The mooring line stress should not exceed the breaking limit *(structural perspective)*.
- The floating collar should not collapse *(structural perspective)*.
- Net volume should maintain at least 60% of non-deformed size *(fish welfare perspective)*.

7.2.2.2 Evaluation of environmental loading

This section demonstrates how the current, wave and wind loads impact the survival conditions of the aquaculture module.

Currents are the dominant type of loading for aquaculture [38, 41]. According to Li, they contribute approximately 75% of the total forces on a medium-sized fish cage mooring system in medium conditions [41], which is similar to the results of the experimental work by Shen [59]. Next to the forces on the loading, Shen states that (in mild conditions) the currents dominate the deformation of the net-cage.

From structural perspective, waves account for approximately 20-25% of total mooring forces [41] and impact the floating collar as well [41]. The Norwegian Design Standard for aquaculture (NS9415:2009) provides very little information about how to treat wave loading, but the subject has received more attention in recent years. In a thesis report published during this project, Stemsrund remarks that the wave-related dynamics of exposed structures are different from those for traditional sheltered structures [61], suggesting that further research is required in this field.

This is emphasised by Shen's findings, which say that for a load case with high current and high waves-steepness, the current no longer dominates and both will have equal contributions to the deformation of the cage [59].

Wind loads affect the aquaculture plant in two ways. Directly, wind loading influences the loading on the cage mooring by approximately 5-10 % through drag on the parts above the surface, like hand-rails, feeding systems and jump netting [41]. Indirectly, it contributes to the loading through wind-induced waves and currents. All in all, wind loads are of lower-order concern for the design of the aquaculture module.

7.2.2.3 Summary of Shen's findings

Figure 7.3 illustrates Shen's findings, which demonstrates that:

- Traditional net-pen systems can function up to 0.85 m/s current speed, which is in the high-exposure range (see also figure I.1)
- A sinker tube limits cage deformation compared to discrete sinker weights.

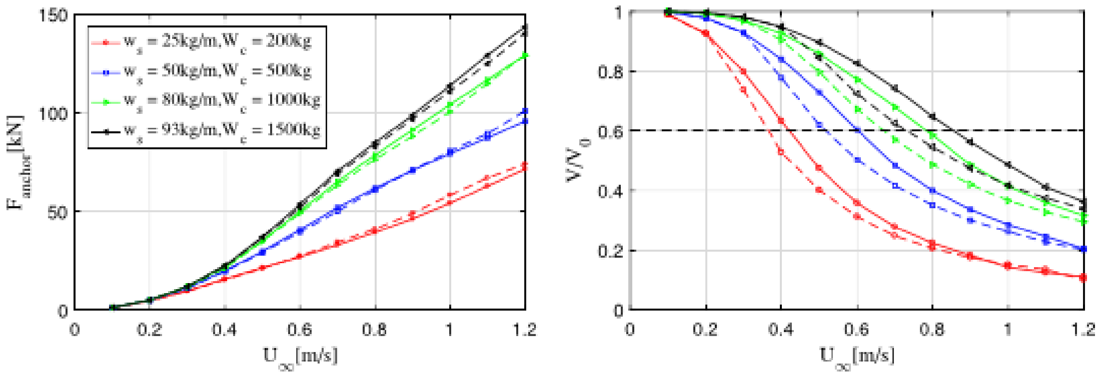


Fig. 7.3 Shen's results regarding mean load (left) and net volume reductions (right) assuming only current loads under different fish farm set-ups. Solid line: sinker tube (w_s). Dashed line: discrete sinker weights (W_s). Right: V_0 is the initial volume of the net cage, V the net volume in steady-state. [59]

Especially the first finding is crucial. Besides, it is useful to shortly echo the other conclusions from Shen. First, he concludes that the floating collar stress is moderate compared to the yield stress, even in extreme states. This suggests that from structural perspective, the multi-use design may be feasible, given that these conclusions hold for a collar of different dimensions under different conditions.

Second, Shen states that the mooring systems currently used can be applied in offshore areas if the bridle lines are properly designed. This conclusion is not critical for the platform design but justifies, from structural perspective, the comparison of the multi-use design with a net-pen based single-use reference concept.

7.2.3 Implications for the further development of multi-use platforms

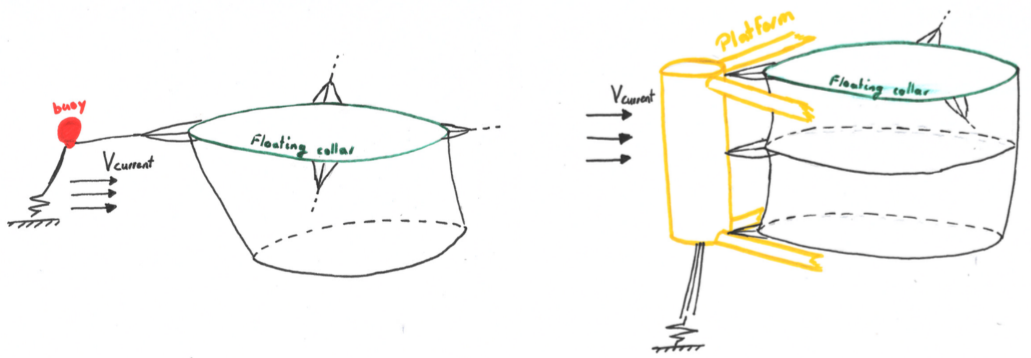
7.2.3.1 Availability of sites

Shen's results show that the net-pen based concept can function up to 0.85 m/s current speed, limited by the deformation of the cage and ultimately fish welfare considerations. First of all, this conclusion helps to evaluate the availability of suitable MUP sites, or the suitability of a chosen design for a specified site with given site conditions.

It should be noted that it remains unclear how the current speed should be treated during the design, that is if incidental exceeding would be acceptable and what would be the design current speed. If the 0.85 m/s current speed corresponds to the 1, 10 or 50-year current return period, this could severely limit the amount of feasible sites [2].

7.2.3.2 Technical development

Shen's conclusions are also relevant for the technical development of this particular concept. A MUP would be particularly interesting if the wind energy module can offer a solution to the deformation issue, which would make the performance superior to the stand-alone system. The presence of a large wind energy structure may provide anchoring points to support bridle lines to support the bottom part of the cage. A suggestion for a design where the cage deformation may be limited is given in figure 7.4.



(a) Traditional net-pen cage mooring configuration (one side only).

(b) New arrangement made possible by attachment to wind energy platform

Fig. 7.4 Comparison of new bridle line arrangement with traditional net-pen deformation

During personal communication with both Richard Langan and Dr. Fredricksson it was concluded that the analysis of such solution requires detailed modelling [40]. If the solution proves effective, that is it helps limit the cage volume decrease, it helps bridge the gap towards the more expensive and challenging fixed netting structures by increasing the range of suitable sites at which the net-pen system can be deployed. Beyond that range, other design solutions or alternative concepts will need to be evaluated.

[2]This statement is based on inspection of confidential site data measured at one particular site which cannot be published in this report. At this particular site, the 50-year current speed is 40% higher than the 1-year current speed.

7.3 Focus area 2: Comparing the mooring loads of the two modules

7.3.1 Approach

By estimating and comparing the loads on the mooring systems of the stand-alone platforms it is aimed at identifying the need for strengthening the MUP mooring design compared to the stand-alone wind energy module. From that, the cost-sharing opportunities can be deduced.

By reviewing literature, a list of reported loads on floating wind energy platforms and both flexible and fixed salmon production cages is made which illustrates the order-of-magnitude of the loading on the stand-alone platforms and moorings. This helps to evaluate how much stronger a mooring system of a MUP would need to be with respect to the stand-alone platforms, which is used as proxy for the cost-saving potential. Note that only the material costs of the mooring are considered. Costs related to the installation of the mooring, are excluded from analysis. Anticipating that flexible nettings may not be suitable for some or many sites, which was learnt from previous section, the loads are compared for both flexible and fixed-type nettings.

The largest cost-saving potential would be attained when it is assumed that one mooring system can bear the load on both the wind energy platform and the net-pen, without modifications. This assumption is based on the premise that the loads on the net-pen are negligible compared to those on the wind energy platform.

However, it is expected that the mooring system of a stand-alone wind energy platform does not allow introducing a net-pen or fixed netting cage structure without modifications, because it would then be over designed. Hence, it is most likely that the MUP mooring system would need to be strengthened, which would also lead to heavier moorings and ultimately more expensive moorings.

7.3.2 Analysis and findings

7.3.2.1 Tabulating the loading values found in literature

Table 7.1 gives an indication of various load values for wind energy structures and aquaculture cages. Do note that the table lists the results of various studies, conducted with different assumptions and input parameters, which stresses the fact that these numbers should be treated as an order-of-magnitude.

Second, some studies provide the mooring load while others provide the horizontal loading on the platform. The translation from loading on the platform to mooring load depends on several parameters (such as mooring weight, water depth, length, angle of attachment and application of load cases) and was not attempted here. This restricts the analysis to separate loading on the platform and mooring load values during the comparison.

Table 7.1 (Estimated) mooring loads on aquaculture and wind energy structures

Structure	Rated power	Netting type	Load type	Load [MN]	Source
Wind Energy					
GustoMSC	5 MW		Mooring line tension (static)	1.49	[23]
GustoMSC	5 MW		Mooring line tension (max)	3.7	[27]
Windfloat	5 MW		Mooring line tension	1.85	[21]
Windfloat	10 MW		Mooring line tension	2.47 - 4.29	[21]
Study concept	5 MW		Horizontal loading	0.8	[71]
Study concept	5 MW		Mooring line tension (max)	3.4	[71]
OC-4Deepwind	13.4 MW		Mooring line tension	3.8	[42]
Salmon farming					
Ocean Farm 1		fixed	Hydrodynamic drag	0.742	[7]
Net-pen cage		flexible	Anchor loading	0.05 - 0.2	[59]
Net-pen cage		flexible	Hydrodynamic drag	0,020	[20]
Net-pen cage		flexible	Design load	0,096	[20]

7.3.2.2 Composition of the loading

The horizontal force on the wind energy platform and salmon cage is a result of the environmental loads acting on the structure. On top of that, the wind energy platform experiences the aerodynamic loading on the wind turbine. In fact, during operational conditions, the aerodynamic loading at rated wind speed is the biggest driver of the load, according to Zhao [71]. In his study, 780 kN out of 800 kN horizontal loading is caused by the wind turbine.

This loading is experienced when the wind turbine is operational. In survival conditions, the turbine is parked and solely the environmental loads act on the platform, including drag on the wind turbine blades and tower. According to Niklas Hummel, these are the design driving load cases for the moorings, but no mooring load data was found where these load cases were considered.

7.3.2.3 Scaling the load to a 20 MW wind turbine platform

The capacity of the platforms in table 7.1 range from 5 MW to 13.2 MW, which is a proxy for their size and loading. To estimate the loading on a 20 MW platform, which is considered in this study, scaling is required.

Scaling the load on the smaller platforms upwards to that of a 20 MW platform is attempted for mooring loads and horizontal loads:

1. Mooring loads: by extrapolating tabulated mooring load data
2. Horizontal loads: by inspecting the thrust curve of the 10 MW DTU reference wind turbine, which is assumed to constitute the majority of loading at rated wind speed.

The mooring loads were estimated by linearly extrapolating the tabulated mooring data, given in figure 7.6. This yields an approximate mooring load of 5.8 MN.
The loading on the platform was estimated based on the assumption that the wind turbine contributes most to the horizontal loading. Hence, the loads on a 20MW platform are estimated by inspecting the thrust curve of the 10MW DTU reference turbine. At rated wind speed, it reads approximately 1500 kN [4]. Hence, a platform with two turbines would lead to an aerodynamic load of 3 MN. Comparing this value with the values presented the table, this seems reasonable.

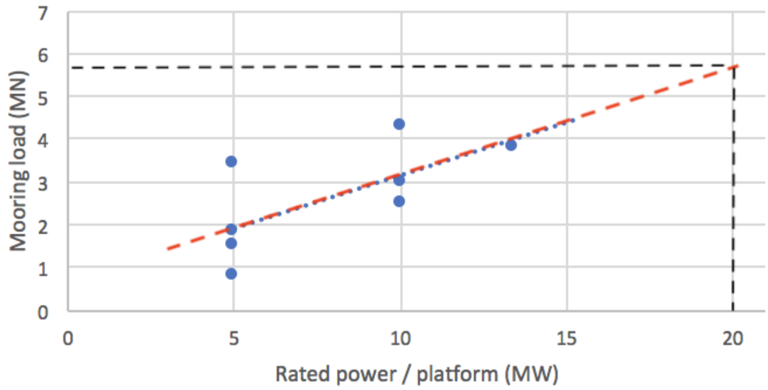


Fig. 7.6 Estimate of the loading on a 20 MW platform based on extrapolation of reference data found in literature

7.3.2.4 Comparison of wind energy and aquaculture loads

Comparing horizontal loading of the wind energy platform to the flexible net-pens yields a very large difference. The aerodynamic loading on two 10 MW DTU reference wind turbines at rated power equals 60-150 times the drag on the netting of a traditional net-pen. However, for the fixed structure Ocean Farm 1, it can then be seen in table 7.1 that the loading on the fixed structure is similar to that of the 5 MW semi-submersible considered by Zhao[71]. Still, a factor 4 difference with the aerodynamic loading is observed.

Comparing mooring load values is difficult because mooring load values for aquaculture were not readily available in literature. Inspection of test results by Zhao [71] suggests that the maximum mooring load can be 4 times larger than the horizontal load. If we assume this factor as representative, the maximum mooring load on flexible netting structures equals approximately 0.4 - 0.8 MN. This would equal approximately 10% to 20% of the tabulated wind energy mooring loads. If the 20 MW structure is considered, in which we are ultimately interested, a factor 7 or 14 difference is observed.

The mooring loads for Ocean Farm 1 could not be found in literature. Because the fixed netting does not deform when it is exposed to currents, it is unlikely that the multiplication factor to estimate mooring loads applies to this structure as well, which leads to the conclusion that this could not be analysed.

7.3.3 Implications for the further development of the multi-use platform

7.3.3.1 Engineering challenges

The previous demonstrates that for flexible netting structures, the impact on the MUP mooring design will be minimal. However, fixed netting configurations will require significant adjustments to the MUP mooring design with respect to the stand-alone reference. Additional challenges to the design of the mooring are that coordination is required in an early stage, and that the increased size of the mooring could potentially complicate fabrication and installation of the mooring.

7.3.3.2 Cost-reduction opportunities

The engineering considerations imply that definitely for fixed netting cages, there is limited cost reduction potential related to the material costs of the moorings, because the benefits of having one mooring instead of two will be partially or fully negated by having to redesign the mooring, which requires more material.

Because the loads of flexible nettings are very small compared to those on the wind turbine, it can be expected that in this case the technical design of the mooring of the multi-use platform will not differ much from the mooring of a single-use wind energy platform. Therefore, it is likely that the additional costs incurred are small compared to the costs incurred for fabrication of a separate mooring for the net-pen cages. Because mooring systems for stand-alone net-pens are expected to become much more expensive when they operate in exposed areas, this is in interesting opportunity.

For fixed-netting structures, the additional costs due to strengthening of the mooring are much larger. Hence, it can be expected that the cost reduction potential will be lower for this type of structures.

While previous opportunity focused on material costs, reduction of installation costs related to the moorings is still an interesting area for further study. However, estimation of these costs requires a better understanding of the reference concepts and more detailed technical specifications, which are not available at this time.

7.4 Focus area 3: Reducing O&M fleet costs

7.4.1 Approach

Evaluating potential cost reductions in vessel fleet selection starts with an overview of activities and vessels for operation and maintenance of a multi-use farm, which is given in section 7.4.2.1. From this overview, different types of activities can be distinguished, which helps to identify opportunities for shared transport during O&M activities.

Before cost assessment can be attempted, more study is required into the planning and time-criticality of these activities, which is discussed in section 7.4.2.2. Section 7.4.2.3 combines and compares the O&M needs of wind energy and aquaculture to obtain better insight in the opportunities for cost-sharing in multi-use configurations based on both vessels and time-criticality.

After this first analysis, a method is proposed in section 7.4.2.4 to estimate the cost-sharing potential by isolating vessel charter costs. Two case-studies are chosen to demonstrate the difference between near-future (near-shore) sites and potential far-future (far-offshore) sites, outlined in table 7.2. For each case the potential cost-savings are estimated in an optimistic, neutral and pessimistic scenario of which the results are presented in section 7.4.3.

Table 7.2 Overview of the two case-studies

Site	Distance to shore	Vessel eligible for cost reduction
Near shore	5 km	Workboats
Far-offshore	100 km	Workboats + SOV

7.4.2 Analysis

7.4.2.1 Outlining O&M activities

Studying the sharing potential of vessels starts with outlining the various types of vessels and the activities for which they are intended.
The distance of the site to shore is an important parameter for choosing appropriate maintenance strategies and the corresponding fleet. Therefore, two cases are evaluated: one near-shore case (e.g. 5 km from shore) and one far-offshore case (e.g. 100 km from shore)

In general, near-shore sites operate from an onshore base. The travel distance and time from shore to the site is short compared to far-offshore sites, leading to for instance lower fuel costs, lower downtime costs and lower response time in case of failure. Both for wind energy and aquaculture, smaller tasks can be serviced with small crew transfer vessels (CTVs) or workboats.

It is expected that in the near future, near-shore sites will be utilized first. Hence, the results from this case-study are more readily applicable. Farther into the future, it is expected that availability of suitable near-shore sites will become a problem, because many sites:

- are used for other purposes (such as fisheries, natural reserves, leisure and shipping)
- pose conflicts with nature (e.g. collisions of wind turbines with birds or interaction with wild salmon)
- are sub-optimal for the combination of wind energy and aquaculture (section 6.3.2.3 adresses this concern).

Therefore, far-offshore sites are also considered, which influences the O&M strategy. For instance, an operator can opt for permanent offshore accommodation, service operation vessel (SOV) and/or helicopters. These options are more expensive, but the benefits of their presence on site rather than operating far from shore (e.g. lower downtime costs) can outweigh the additional expense. Offshore-based O&M strategies for the wind energy sector are only recently being developed, therefore reference costs are not readily available which makes estimates less reliable.

For the near-shore case, an overview of activities and the corresponding vessels is given in table 7.3. The last column indicates that for smaller tasks (such as replacement of small parts, lubrication of moving parts, or inspection) the same vessels are used and could therefore potentially be shared among the users of a multi-use farm. For the far-offshore case, the SOVmay be used to serve as offshore accommodation and storage place for small spare parts, but is not included in the table.

Table 7.3 Overview of O&M categories, vessels for wind energy and aquaculture and potential for vessel sharing. The categorization of O&M activities is adapted from Asgarpour and Sørensen [3])

Activity (type)	Vessels - wind energy	Vessels - aquaculture	Potential
minor corrective	workboats	workboats	✓
major corrective	heavy-lift / jack-up / tug-boat	support vessels	×
minor preventive	workboats	workboats	✓
major preventive	heavy-lift / jack-up / tug-boat	support vessels	×
inspection	workboats	workboats	✓
feeding refill	n.a.	specialised feeding vessels	×
de-lousing	n.a.	specialised workboats	×
transport of smolt	n.a.	specialised well-boats	×

7.4.2.2 Differentiating between activities

Whereas aquaculture requires more *planned* visits for inspection and operational tasks, wind energy requires more *unplanned* visits for corrective maintenance. The distinction between planned and unplanned visits is crucial for the realisation (and estimation) of the potential for sharing transportation infrastructure between operators in a multi-use farm. Figure 7.7 schematically illustrates the two types. which can in turn be divided into *time-critical* and *non time-critical* activities.

Planned visits can be coordinated among the two users of the farm, and would relatively easy allow cooperative use of transport vessels. Unplanned visits include visits which could not have been foreseen, for instance due to failure of a component, but may also denote an activity which was originally planned but had to be postponed and doesn't fit the schedule any more. Although not denoted in figure 7.7, planned visits may also be time-critical, but are here assumed to be executed at the right time. If, due to some unexpected event, the planning is compromised, the required activity can be thought of as an unplanned event.

It is expected that plannned activities offer opportunities for sharing of transportation infrastructure. The problem for sharing infrastructure in a multi-use environment lies in unplanned

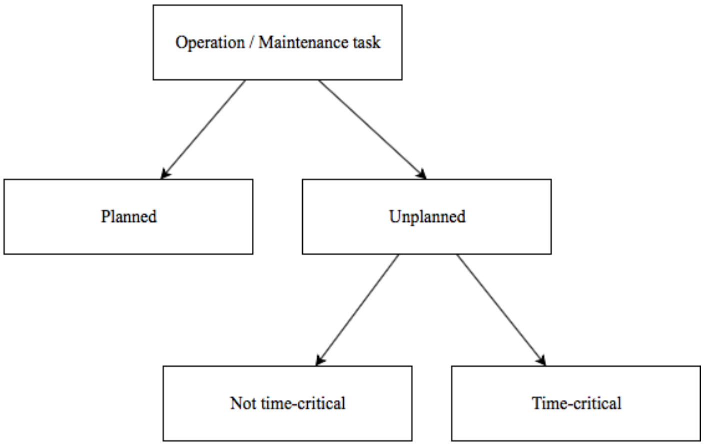


Fig. 7.7 Distinguishing between planned, unplanned O&M activities and time-criticality

and time critical activities.

Time-critical activities and their influence on MUP O&M logistics
In wind energy, corrective maintenance of wind turbines is a time-critical activity. Although strategies are proposed where turbines are repaired in batches, or not repaired at all [57], most wind farm operators choose to repair a turbine immediately to limit downtime costs. This is referred to as the "repair on failure" maintenance strategy. This means that after turbine failure, when a suitable weather window and required spare part are available, a vessel needs to be available to avoid unnecessary downtime.

Similar time-critical activities exist for aquaculture. According to Ryan and Langan, feeding of the fish is such a time-critical activity [40]. Ryan states that failure to feed on time for just 10 days per year can lead to significant reductions in production output [53, p. 57]. Although feeding of the fish is a planned activity, exposed conditions and unavailability of weather windows can lead to a tight schedule as soon as a weather window becomes available. Because many platforms will then need to be serviced simultaneously, unavailability of vessels is likely and not desirable.

Another example of a time-critical activity is repair of a netting structure after failure, which requires quick response time to prevent (or limit the number of) fish from escaping.

In such cases, or especially when both on wind energy and aquaculture side fast action is required, logistical issues may arise due to double-booked vessels. This risk is amplified because since the weather conditions for wind energy and aquaculture will by definition be the same when operating at the same site, this increases the chance of having double-booked vessels due to overlapping weather windows.

Non time-critical activities
Actions required due to unplanned events which do not require immediate response, hence which are not time-critical, could be planned based on opportunity. Opportunity-based maintenance entails that the required action is delayed until a vessel is scheduled to go to (or near) that platform for another scheduled activity. For MUPs, this could be an attractive strategy, especially because the weather windows are aligned which means vessels are likely to travel at the same time.

7.4.2.3 Analysing opportunities for shared transport related to O&M activities

Comparing the categories of activities and vessels required for each activity obtained in the previous sections helps to give an indication of the sharing potential in a multi-use configuration. Figure 7.8 aims to illustrate the combinations of activities where shared crew transport and thus reduced vessel charter costs can be realised. Note that not all aquaculture-specific tasks are evaluated because they require highly specialised vessels.

		AQUACULTURE						
		Corrective maintenance		*Preventive maintenance*		*Operation*		
		minor	major	minor	major	inspection	feed supply	husbandry tasks
WIND ENERGY *Corrective maintenance*	minor	T	T	O	V	O	O	O
	major	T,V	T,V	O	O	V	V	V
Preventive maintenance	minor	O	T	S,O		S,O	S,O	S,O
	major	V	T	O	O	V	V	V
Operation	inspection	T	T	S,O	S,O	S,O	O	O

Limiting factor
T = time-criticality
V = vessel type

Sharing type
O = opportunity-based
S = scheduled

Potential
Very low | Limited | High

Fig. 7.8 Schematic analysis of the activity-based potential for sharing vessels to MUP platforms

In case that sharing potential is identified, indicated by orange and green colours, the figure indicates whether the sharing can be scheduled or is opportunity-based. If no potential sharing opportunity is expected, indicated in red, the limiting factor is given which can be either time-criticality or use of a different vessel. Some activities require a specialised vessel designed for one activity but not appropriate or overkill for the other. For instance, using the heavy-lift vessels for a wind turbine gearbox replacement are an overkill for lifting a netting structure, and due to their very high day-rates are not likely to be used for that purpose.

This analysis results in the following types of vessel-sharing opportunities:

1. Scheduled (+ opportunity-based) inspection visits
2. Scheduled (+ opportunity-based) preventive maintenance
3. Opportunity-based combinations of various activities

It is expected that the combination of minor corrective maintenance of wind energy and aquaculture does not offer sharing potential due to the time-criticality of the repair and the fact that the chance of one platform requiring corrective maintenance at the same time is considered small. The same holds for major corrective maintenance tasks, which also require different types of vessels and are therefore not likely to lead to cost-sharing opportunities.

7.4.2.4 Selecting a suitable cost estimation method

It is desired to obtain a first estimate of the potential cost-reduction associated to shared use of vessels. Cost estimation models for wind energy can typically be divided into stochastic and deterministic models. For this purpose, a deterministic approach was chosen which is based on simple assumptions highlighting the main considerations and ensuring transparent results.

Although the deterministic approach fails to deliver detailed insights, for which the stochastic approach is better suited, it can provide an estimate of the boundaries of the cost-sharing potential for vessels under various assumptions. Besides, the stochastic models which could deliver such insights are much more complex and time-consuming than deterministic models, which has been an important driver for the decision to opt for the deterministic approach. This choice imposes the limitation that study of opportunity-based maintenance and the impact of time-critical events and weather windows on O&M costs is not possible, because this requires studying the timing of the events which only stochastic models can capture.

It should be noted that only the vessel costs will be calculated and not the total O&M costs. After the cost-savings estimate is developed, the savings are compared to gross values of O&M costs to study the impact on total operating expenditure and ultimately on the production costs of energy.

7.4.2.5 Estimating total vessel costs

Using the deterministic approach, the following method is proposed to obtain a gross estimate of the boundaries of the potential. This requires an estimate of:

- the type and number of vessels required in the multi-use farm and the stand-alone activities.
- the charter rates and duration of the vessel charter.
- the price increase of MUP vessels with respect to single-use vessels.

The total costs of vessels for the single-use activities are calculated as:

$$C_{stand-alone} = N \cdot R_{charter} \cdot T_{charter} \tag{7.1}$$

where $C_{stand-alone}$ = total vessel costs, N = number of vessels, $R_{charter}$ is the charter rate and $T_{charter}$ is the duration of the charter.

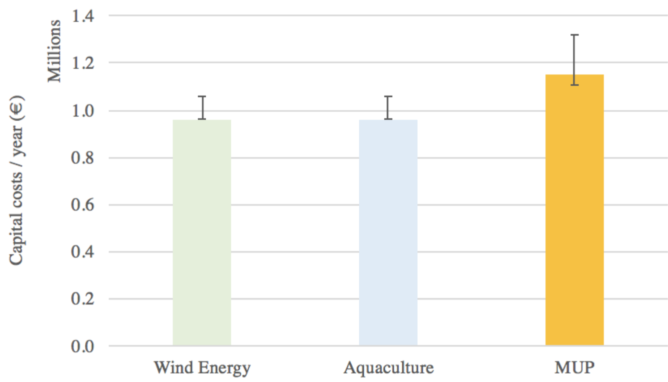
Estimating the costs of multi-use vessels uses the same method but requires an assumption to estimate the cost increase of multi-use vessels with respect to single-use vessels. This is because it cannot be assumed that a vessel designed for wind energy can host additional crew, and vice-versa. During an interview with Damen Shipyards it was confirmed that multi-use vessels will require additional features and adjustments to comply to regulations. Inspection of the specifications of today's workboats presented in appendix F revealed that more space is required to host more crewmembers on board, which leads to additional costs. To cover this cost increase, a cost multiplication factor of 20%-30% is estimated, which was established during an interview with Damen Shipyards [70].

This leads to the following expression for the costs of multi-use vessels:

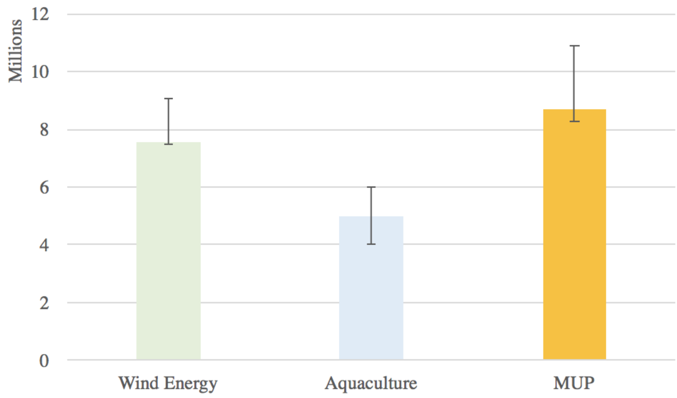
$$C_{multi-use} = N \cdot R_{charter} \cdot T_{charter} \cdot \alpha \tag{7.2}$$

where $C_{stand-alone}$ = total vessel costs, N = number of vessels, $R_{charter}$ is the charter rate and $T_{charter}$ is the duration of the charter, and α equals the MUP multiplication factor of 20%.

The vessel charter rates presented in figure 7.9a are obtained from literature and were validated by data kindly provided by Damen Shipyards [70] and ECN part of TNO [62] during two separate interviews. It should be noted that the value for aquaculture workboats could not be obtained and are assumed equal to that of wind energy, a reasonable first assumption according to Damen Shipyards. The costs for an aquaculture-specific SOV is assumed smaller than that of wind energy due to the lower crane capacity and expected lower spare parts storage requirements. The higher costs of the MUP vessels result from the cost multiplier of 20%. The expected uncertainty in the values is indicated by the whiskers, and is largely based on the slight differences in values that were obtained in literature and during the interviews.



(a) Workboats / Crew Transfer Vessels



(b) Service Operation Vessels

Fig. 7.9 Charter rates for two vessel types

Lastly, and most importantly, the number of vessels which are required to operate the farm is required. The difficulty here lies in estimating how many vessels can be saved in a multi-use platform, with respect to the sum of the stand-alone activities, assuming that availability and salmon growth remain equal and are not affected by having fewer vessels. For both the near-shore and far-offshore case, three scenario's were considered to demonstrate the cost-savings under different assumptions. Tables 7.4 and 7.5 provide an overview of the inputs, of which the resulting costs are presented in next section.

Table 7.4 Scenario set-up for near-shore case

Scenario	Variable	Aquaculture	Wind Energy	MUP	Vessels saved
Optimistic	Nr. of workboats	3	3	3	3
	α			20%	
Neutral	Nr. of workboats	3	3	4	2
	α			20%	
Pessimistic	Nr. of workboats	3	3	5	1
	α			20%	

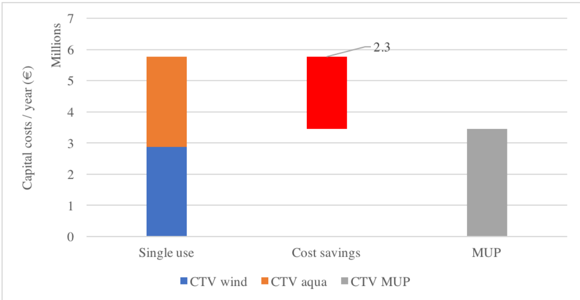
Table 7.5 Scenario set-up for far-offshore case

Scenario	Variable	Aquaculture	Wind Energy	MUP	Vessels saved
Optimistic	Nr. of workboats	3	3	3	3
	Nr. of SOV's	1	1	1	1
	α			20%	
Neutral	Nr. of workboats	3	3	4	2
	Nr. of SOVs	1	1	1	1
	α			20%	
Pessimistic	Nr. of workboats	3	3	5	1
	Nr. of SOVs	1	1	1	1
	α			20%	

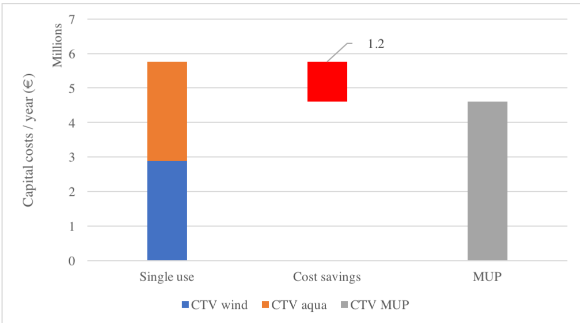
7.4.3 Findings

7.4.3.1 Cost-saving potential for the near-shore site

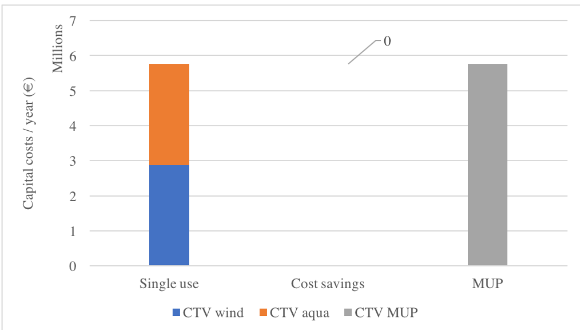
Figure 7.10 illustrates the cost-saving potential under the scenario's tabulated in table 7.4. It compares the sum of the costs for the single-use activities (left) to the costs in the multi-use configuration (right). The difference between the two marks the total cost saving (middle).



(a) Optimistic scenario



(b) Neutral scenario

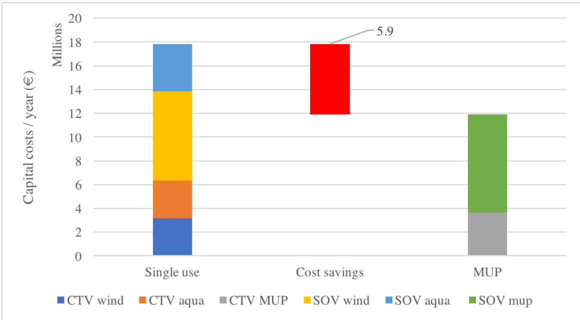


(c) Pessimistic scenario

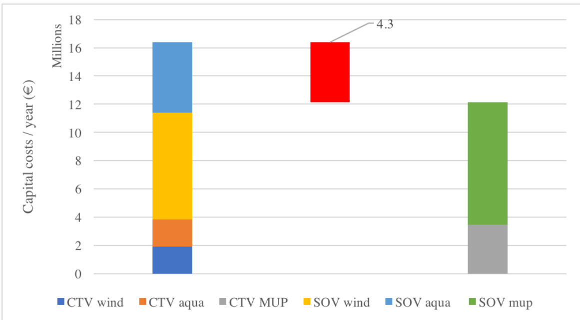
Fig. 7.10 Cost saving potential for the near shore site under three different scenario's

7.4.3.2 Cost-saving potential for the far-offshore site

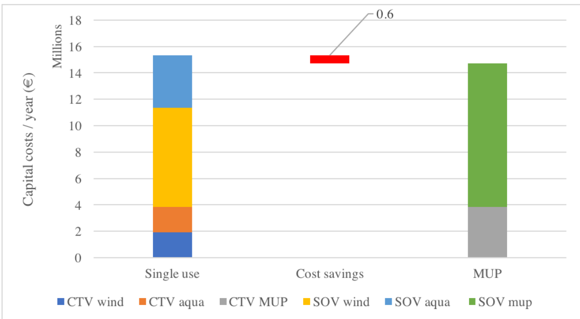
Similarly, figure 7.11 illustrates the cost-saving potential under the scenario's tabulated in table 7.5.



(a) Optimistic scenario



(b) Neutral scenario



(c) Pessimistic scenario

Fig. 7.11 Cost saving potential for the far-offshore site under three different scenario's

7.4.3.3 Interpretation of results

The findings discussed in the previous section suggest that in the near-shore case, a maximum total cost-reduction of €2.3 million per year can be achieved. If this cost-reduction is assumed to be split equally between both parties, this would correspond to a €1,15 million euros cost saving per annum for both wind energy and aquaculture in the optimistic scenario. While optimistic, this is also unlikely. More likely is the neutral, or perhaps the pessimistic scenario, in which two vessels or only one vessel can be shared among the users of the farm. This results in a much smaller cost-reduction opportunity.

It is useful to compare the estimated cost-reduction potential against the total expenditure of both wind energy and aquaculture.

On the wind energy side, the 560 MW Hexicon case-study presented in figure 7.3a is used as reference. In the case study, crew transport is estimated at approximately 6% of OPEX. Due to confidentiality reasons, exact numbers cannot be disclosed. However, the cost-reduction potential would range between 0% and 20% of vessel costs which translates approximately to 0% (pessimistic), 0.7% (neutral) and 1.4% (optimistic) of OPEX. Considering that operational expenditure contributes approximately 20-30 % of LCOE, the effect on the production cost of energy is very small.

On the aquaculture side, no suitable reference for comparison was found, but a similar or smaller result is expected. That is primarily because vessels are part of CAPEX, which constitutes a relatively small share in the production costs of salmon and is dominated by licence costs and the cage structure.

It should be noted that the scenario-based calculations were made under the assumption that energy yield and salmon yield would remain unaffected by having fewer vessels. It can be expected that if this assumption is not valid, the cost-reduction opportunity would vanish.

7.4.4 Implications for the further development of MUPs

7.4.4.1 Cost-reduction opportunities

The results show that there exists a potential for cost savings in near-shore multi-use farms by sharing workboats for O&M activities. This potential is larger at far-offshore sites, where joint use of an SOV can additionally be considered. Due to the cost increase of multi-use workboats with respect to single use vessels, and the limited number of vessels with which the fleet can be reduced, the cost savings at near-shore sites are limited. It has been demonstrated that saving one out of six vessels not necessarily leads to cost-reductions due to the added costs of MUP vessels with respect to single-use vessels.

Lastly, it should be noted that this result does not (directly) apply to share-space multi-use configurations (see also section 5.2.1) Share-space concepts require more boat landings and crew transfers, hence it is likely that their potential reduction in fleet size are smaller than for shared-platform concepts, which leads to lower cost-reduction opportunities.

7.5 Focus area 4: Inhibiting the tow-to-shore strategy

7.5.1 Approach

No method or benchmark was found in literature to estimate the cost-savings related to the tow-to-shore strategy. Therefore, a simple method was used to obtain a coarse estimate of the cost savings of this strategy compared to chartering expensive heavy-lift vessels. The method, cost-estimates and assumptions were briefly checked by ECN part of TNO and are shortly outlined below [62].

The first step is to specify the type and number of maintenance actions. It was chosen to consider only preventive maintenance, which is assumed to take place once every 5 years for every turbine. Hence, for a farm consisting of 80 turbines, this equals 16 major repairs per annum.

An estimate of costs can then follow. Because it is attempted to demonstrate the difference between the two strategies, all costs which cannot distinguish between the two, such as the costs of spare parts, are not considered. The sum of distinguishing costs will be named total logistics costs, which should not be confused with total major repair costs.

The next section presents how the costs are estimated for the stay-offshore strategy and tow-to-shore strategy.

7.5.2 Analysis

7.5.2.1 Stay-offshore strategy

The costs of performing maintenance offshore were calculated as the summation of vessel costs and downtime costs.

$$C_{total} = C_{jack-up} + C_{downtime} \tag{7.3}$$

The jack-up vessel costs were calculated as the product of the charter rate per day and number of days it is needed. Because large-scale preventive maintenance actions are planned in advance, the assumed vessel rate is lower than that on the spot market and only one mobilisation rate is charged.

The downtime costs are calculated as follows:

$$C_{downtime} = T_{down} \cdot P_{installed} \cdot 365 \cdot 24 \cdot C_f \cdot X \tag{7.4}$$

where $C_{downtime}$ = total downtime costs, T_{down} = total downtime, $P_{installed}$ = installed capacity, (365*24) = nr. of hours in a year, C_f = capacity factor =0.45, X = electricity price

Of which the downtime is assumed to be the sum of the repair time, weather delays and waiting time caused by other events such as unavailability of vessels.

$$T_{down} = T_{repair} + T_{waitingtime} + T_{weatherdelay} \tag{7.5}$$

7.5.2.2 Tow-to-shore strategy

The tow-to-shore strategy replaces the expensive jack-up for much cheaper tug-boats. In addition, harbour costs are charged for performing the repair on shore. The total costs for this strategy are calculated as:

$$C_{total} = C_{tug-boat} + C_{downtime} + C_{harbour} \tag{7.6}$$

It is assumed that three tug-boats are required for each platform. Considering tug boat speed and distance from shore, it is estimated the transport can be done in one day which adds up to two days per repair.

$$\begin{aligned} C_{tug-boats} = T_{active} \cdot (R_{active} + C_{Fuel}) + T_{stand-by} \cdot R_{stand-by} \\ + N_{tugs} \cdot C_{mob.} + N_{tugs} \cdot C_{demob.} \end{aligned} \tag{7.7}$$

The harbour rate was obtained at ECN part of TNO and is assumed 25.000 €/day. A conservative 240 days per year are assumed to account for weather delays in between repairs.

$$C_{harbour} = T_{harbour} \cdot R_{harbour} \tag{7.8}$$

The downtime costs are given by 7.4 where the downtime equals:

$$T_{down} = T_{time-to-shore} + T_{repairtime} + T_{time-to-site} + T_{weatherdelay} \tag{7.9}$$

The downtime costs of the tow-to-shore strategy are slightly higher than those for the stay-offshore strategy because the platform needs to be towed to shore and back.

Furthermore, this strategy requires two good weather windows instead of one for the jack-up vessel. At the same time, the probability of having this weather window is higher because the required window is 1 day instead of 5. Because this influence is uncertain, weather delays are assumed equal for both cases.

7.5.2.3 Key assumptions, inputs and outputs

The following tables summarize the assumptions, inputs and outputs which were used to calculate the total logistics costs for major repairs. An overview of the findings is presented in section 7.5.3.

Table 7.6 General input values and vessel costs for the calculation of the costs of two major maintenance strategies. Vessel cost data has been reviewed by ECN part of TNO [62].

General input values	Value	Unit
Repair frequency	0,2	turbines / year
Number of turbines	80	
Number of repair actions	16	actions/year
Jack-up charter rate (incl. fuel)	125.000	€/day
Jack-up mobilisation rate	920.000	€
Towing vessel rate	12.000	€/day
Towing vessel standby rate	8.500	€/day
Towing vessel mobilisation rate	75.000	€
Towing vessel demobilisation rate	75.000	€
Towing vessel fuel costs	12.000	€/day

Table 7.7 Calculating downtime costs for two major maintenance strategies

	Stay offshore	Tow to shore	unit
Repair time	5	5	days / platform
Total waiting time (e.g. crew, parts)	5	-	days
Total weather delay	20	20	days
Total towing time	-	2	days
Total downtime	**105**	**137**	**days**
Power (exposure)	10	20	MW
Capacity factor	0,45	0,45	
Electricity price	50	50	€/MWh
Total energy loss	11.340	29.592	MWh
Total Downtime costs	**576.000**	**1.479.600**	**€**

Table 7.8 Calculating vessel and harbour costs for two major maintenance strategies

	Stay offshore	Tow to shore
Jack-ups	1	
Jack-up mobilisations	1	
Duration of charter	107 days	
Total jack-up costs	**€14.295.000**	-
Towing vessels		3
Towing vessel mobilisations		3
Towing vessel demobilisations		3
Charter - active		192 days
Charter - stand-by		20 days
Total towing vessel costs	-	**€5.228.000**
Harbour rate		€25.000 / day
Days in harbour		240 days
Total harbour costs	-	**€6.000.000**

7.5.3 Findings

The yearly expenditure for the two strategies, excluding the costs of e.g. spare parts, is displayed in the bar-chart in figure 7.12. The outcome suggests that, based on this particular set of assumptions, the tow-to-shore strategy leads to an approximate €2 million savings on major repair costs per annum.

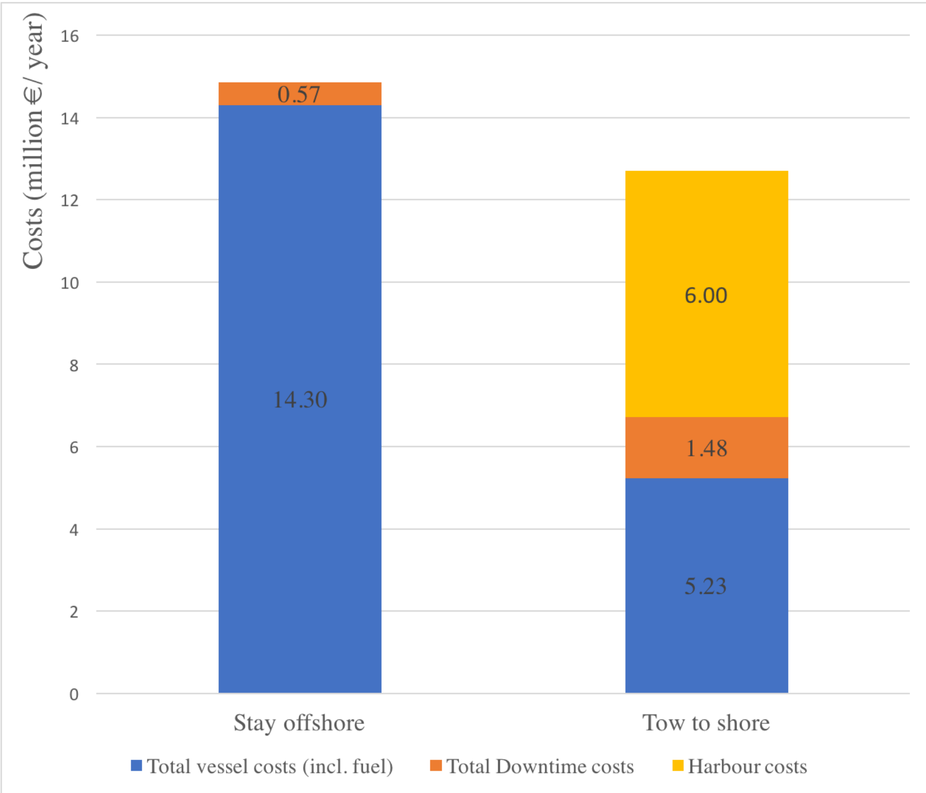


Fig. 7.12 Total logistics costs for two major repair strategies

7.5.4 Implications for the further development of MUPs

At present, it is thought that the presence of the aquaculture module inside the wind energy platform prohibits the tow-to-shore strategy. This prevents a potential cost-saving for the multi-use farm which the stand-alone wind energy concept would benefit from and could thus be a potential show-stopper.

On the other hand, it should be noted that the tow-to-shore strategy has not been proven in existing wind farms and is a proposed strategy in favour of floating wind energy. It is expected that floating wind energy projects will initially continue to use established maintenance strategies requiring the use of heavy-lift vessels. Hence, the outcome of this estimate should not weight too heavily on the evaluation of the MUP, but should be taken into account.

Lastly, note that this finding applies exclusively to floating wind energy structures, as bottom-founded structures will anyways require the use of expensive heavy-lift vessels.

7.6 Update of threats and opportunities

With the newly obtained information, this section provides a concise update of the list of threats and opportunities in table 7.9, which was first presented in section 6.4. The updated version is suggested for future reference. The changes are listed below.

- The estimate of the threat that traditional net-pen cages are not suited for exposed environments has been downgraded, because a better estimate of operational limits is obtained.
- The estimate of the opportunity for cost-reduction in mooring costs has been downgraded because the cost-reduction potential was lower than expected.
- The estimate of the opportunity for cost-reduction in vessel-sharing costs has been downgraded because the cost-reduction potential was lower than expected.
- The estimate of the threat that the tow-to-shore strategy may be a showstopper has remained equal, because the results matched the expectations

Table 7.9 Identified opportunities and threats in relation to the main objectives

	Magnitude	Objective
Opportunities		
Learn from limit state design methods	+	Engineering
Cost-reduction through site survey data gathering	+	Costs
Knowledge transfer	+	Engineering
Mooring material and installation cost reduction	+	Costs
Sheltering effect may alleviate fish stress	+	Salmon Yield
More suitable weather windows due to boat landing facility	+	Salmon Yield
More suitable weather windows due to stable platform	+	Salmon Yield
Cost-reduction opportunity of O&M vessel charter	+	Costs
Cost-reduction through joint installation strategy	+	
Threats		
Traditional net-pen not suited for exposed environments	- -	Engineering, Costs
Non-availability of optimal site conditions for both activities	- - -	Energy Yield, Salmon Yield
Moorings need to be strengthened because of additional structure and increased biofouling rate	-	Engineering, Costs
Hydrodynamic response of the coupled cage and platform	-	Engineering
Sheltering effect may reduce oxygen and feed dispersion	-	Salmon Yield
Heave, roll and pitch motion may leed to stress for the fish	-	Salmon Yield
Tow-to-shore strategy may be compromised w.r.t. stand-alone wind energy	- -	Costs
Availability of wind turbines should not be reduced by aquaculture operations	- - -	Energy Yield

Chapter 8

Conclusions and Recommendations

This chapter presents conclusions and recommendations which aim to guide future efforts in the development of multi-use platforms, in particular related to integrating salmon production in offshore wind farms. After an introduction, summarizing the contribution of previous chapters to the overall research objective, conclusions regarding methodology and results are presented. Subsequently, recommendations are given for improvement of the methodology and to further develop the multi-use concept.

8.1 Introduction to the conclusions and recommendations

Multi-use of offshore platforms is a long-term research challenge which aims to combine food and energy production at sea. Research in this field is in its infancy, literature is scarce and without much cross-referencing. The aim of this thesis has been to develop a coherent set of recommendations for the further development of multi-use platforms, specifically for offshore floating wind energy and salmon aquaculture.

Chapter 2: Background provided a short introduction to the two activities and a brief overview of previous work on multi-use concepts. The main philosophy of this research, outlined in *Chapter 3: Research Methodologies*, has been that a design-oriented approach can be used to generate insights regarding multi-use platforms. In this regard, *Chapter 4: Conceptual Design Methodology* proposed a framework to do this in a structured manner.

New multi-use concepts were generated and presented in *Chapter 5*, illustrating what a future multi-use farm could look like. Simultaneously, a rigorous decision-making framework was set-up aimed at identifying a superior concept, while systematically producing insights by making explicit the trade-offs which govern the decision. *Chapter 6: Preliminary Design Evaluation* evaluated the preferred concept in more detail by focussing on the identification of engineering challenges and cost-reduction opportunities.

This chapter first presents conclusions regarding the effectiveness of methodology that was used, and subsequently draws conclusions related to the further development of multi-use wind farms. In the same order, recommendations are presented to improve the methodology and subsequently to further the development of multi-use wind farms in the quest for spatial efficiency.

8.2 Conclusions

8.2.1 Conclusions related to the methodology

The methodology which was used is considered effective, based on two attributes. First, its ability to present, evaluate, compare and rank a diverse range of new alternatives. Second, its ability to produce insights regarding multi-use concepts during these various stages.

The components of the first attribute are discussed one-by-one. First, the creative stage stimulated to come up with a diverse range of alternatives, which led to the conclusion that there exist many alternatives for multi-use, each with different properties. Identification of these properties, in consultation with relevant experts, led to a list of evaluation criteria which is considered useful for future analysis of multi-use concepts.

Comparing the alternatives based on their performance on these criteria provided insight in the relevant trade-offs. Although many decisions have an intuitive component, the framework ensures that for each criterion an explicit judgement is required. This is useful input for discussions with different stakeholders during decision-making and also inherently documents decisions for future reference.

The ranking stage was aimed at identifying a preferred concept, based on the judgements made in previous steps. To obtain an order of preference, a Multiple Criteria Decision Analysis (MCDA) approach was followed and complemented by visual mapping of criteria scores. Uncertainty in the articulation of stakeholder preference was introduced by stochastic sensitivity analysis based on Monte Carlo simulations. The key methodology-related conclusions drawn from this stage are:

- The sensitivity analysis method proposed by Butler et al. was successful in identifying a subset of superior alternatives, which was confirmed by visual inspection of the criterion space.

- The sensitivity analysis method proposed by Hyde was successful in identifying different preferred configurations for the operator and for society.
- Introducing uncertainty has, in this case, no effect on the final suggested ranking obtained through MCDA, but nuances the view that certain alternatives are the single-best options.

The objective of *Chapter 6: Preliminary Design Evaluation* has been to generate more detailed insights into the technical challenges and cost-reduction opportunities for multi-use platforms. A key philosophy here was to compare the preferred multi-use platform against stand-alone wind energy and aquaculture, primarily aimed at discovering the differences and isolating those areas for further study. This approach was effective for distillation of relevant multi-use related aspects from a much larger range of challenges for floating wind energy and exposed aquaculture. A list of opportunities and threats was developed and presented in section 7.6. This list may be used to guide future efforts regarding the development of both the preferred concept and multi-use platforms in general.

The second point which contributes to the effectiveness of the framework, the ability to produce insights regarding multi-use platforms, is supported by the findings presented in the next section.

8.2.2 Conclusions related to the results

Except for one item, no major technical barriers for the further development of multi-use platforms were identified, given that the challenges associated to the stand-alone activities can be met. This item is the expectation that mooring loads will largely increase by integrating fixed-netting structures in wind energy platforms. A small set of cost-reduction opportunities was discovered, as well as threats to the economic viability.

This section first lists three main conclusions which can be drawn, followed by supporting conclusions drawn from the four key focus areas.

- The comparison between stand-alone reference concepts and multi-use designs was based on the assumption of achieving equal salmon and energy yield. Section 6.3.2.3 stressed that sites optimal for wind energy may be sub-optimal for aquaculture, and vice-versa. Hence, the potential scarcity of sites which are optimal for both activities challenges the validity of this assumption, and therefore the feasibility of multi-use platforms.

- Evaluation of the cost-reduction opportunities nuanced the view that large cost-reduction opportunities exist in mooring design and shared O&M vessels. It was demonstrated that the multi-use concept can also lead to additional costs.

- Although the cost savings may not be the biggest advantage of MUPs, the potential for knowledge transfer and sharing of environmental site data was identified as additional benefit.

Related to the key focus areas, the following supporting conclusions are drawn.

The first focus area addressed the concern that traditional net-pen aquaculture cages may not be suitable for exposed environments, a research area which only recently received attention. It was found in literature that the use of traditional net-pen systems is limited by volume reduction of the cage at high current speeds and not by structural failure. Therefore, a design solution was proposed to limit cage volume reduction in the multi-use configuration, aiming to increase the tolerance for high current speeds.

Second, comparison of environmental loading on traditional net-pens and Ocean Farm 1 confirmed that the mooring system of a MUP needs to be redesigned with respect to the stand-alone designs. For flexible net-pens, the adjustment is expected to be minimal. For fixed netting structures, large adjustments are required. This result leads to the conclusion that the cost-reduction potential for shared use of the mooring system is smaller than expected, especially for fixed netting structures.

Third, the opportunity for cost reduction in O&M expenditure was investigated, based on the needs and requirements of both wind energy and aquaculture. It was found that the different types of tasks, vessels, and levels of time-criticality limit the potential of sharing transportation infrastructure, which lead to the conclusion that cost savings at near-shore sites are limited to a small part of total expenditure. Far-offshore sites may offer more cost saving potential in absolute terms, but it is unclear how this translates to a percentage of total expenditure.

Fourth, the analysis of O&M strategies pointed out that multi-use concepts can lead to additional costs compared to the stand-alone reference, by inhibiting the tow-to-shore major repair strategy, This can potentially negate the benefits obtained by cost-reductions on vessels and moorings. Other types of multi-use solutions, such as share-space concepts, may allow the tow-to-shore strategy, but will not have the cost-savings in mooring design and less efficient vessel sharing logistics.

All in all, if the challenges for the individual activities floating wind energy and exposed aquaculture are overcome, the quest for increased spatial efficiency is opposed by relatively small additional engineering challenges. From economic perspective, small cost-reductions on one hand and additional costs on the other do not pose a major encouragement for the further development of multi-use concepts, but are also not discouraging [1].

Follow-up is necessary and desired, for which recommendations are given in the next section.

8.3 Recommendations

8.3.1 Related to the improvement of this methodology

There are many ways in which the methodology could be improved. This section presents a list of suggestions, organised into those which concern the conceptual design methodology and those which are related to the preliminary design evaluation. Related to the conceptual design stage:

- The foremost need is the input and expertise of the aquaculture industry to this work. Feedback on the evaluation criteria, the proposed designs and the most preferred design can be expected to lead to new insights.
- Regarding the generation of concepts, performing brainstorm sessions with experts in relevant fields can likely lead to additional and more effective solutions.
- Regarding the evaluation of concepts, re-iteration of the defined set of evaluation criteria is recommended.
- Regarding the comparison and ranking of concepts, a more accurate qualitative definition of the procedure of assigning weights to the criteria may improve the *a priori* articulation of stakeholder preference and reduce (unintended) judgement errors.
- At present, ethical values related to the environment and health of fish and crew are implicitly captured as constraint to other variables but are not made explicit during the

[1] It should be noted that (financial) risk has not been evaluated here, and that the evaluation of costs has not been exhaustive.

decision-making process. Integrating the Value Sensitive Design theory developed at Delft University of Technology may be an effective way of doing so.

Related to the preliminary design evaluation:

- Similar to the conceptual design stage, involvement of a larger range of experts is recommended.
- Related to the economic assessment, risks have not been studied. Inexperience with multi-use logistics and known and unknown interactions introduce risk into the economic assessment of a multi-use platform compared to the stand-alone activities.
- Regarding focus area 1: modelling of the net-pen cage is required to study the deformation and loading. This was suggested by Prof. Langan and Dr. Fredricksson as a topic for future research.
- Regarding focus area 2: calculation of the actual mooring loads for a MUP and similar-sized stand-alone facility is required to more accurately assess the engineering challenge and possible cost-reduction associated with shared moorings.
- Regarding focus area 3:
  - Stochastic modelling of operation and maintenance can provide insights into the feasibility of shared use of transportation infrastructure, by giving insight into scheduling of time-critical events and ultimately the influence of shared vessels on the availability of the wind farm. Additional expertise is required to integrate into such a model the effects on salmon growth.
  - Validation of vessel costs for aquaculture operations is necessary in order to make more confident estimate of potential cost-savings.
- Regarding focus area 4:
  - First, the feasibility of the tow-to-shore strategy should be demonstrated for stand-alone wind energy.
  - Similar to the analysis of O&M vessels, major repair costs depend on time-critical activities and costs are influence largely by waiting times and weather windows. More detailed analysis is required to study the effect of this on the presented cost estimate.

8.3.2 Related to the further development of multi-use farms

This section presents areas in which more research is required to further the development of multi-use farms and thereby provides an open-ended answer to the overall research aim.

- Further study is required into the availability of sites for multi-use. It is likely that sites exist where the two activities can be combined, but finding an optimal location with additional constraints is expected to be a challenge. Whereas wind energy is mostly concerned with having high wind speeds, these often induce higher currents and waves which aquaculture seeks to avoid. Hence, it is likely that an optimal site for wind energy is sub-optimal for aquaculture, and vice-versa. GIS mapping tools are suggested.
- Related to previous point, it is recommended to evaluate designs based on a fixed netting structure, which are known to be better suited to exposed environments but at higher costs. It is expected that fixed structures reduce potential issues regarding site selection by lowering the constraint to current speed.
- It is necessary to investigate whether aquaculture in the wind farm has an effect on availability of the wind turbines, and whether the presence of wind energy affects salmon production.
- It is recommended to study in more detail the advantages and disadvantages of shared-platform and shared-space concepts, outlined in section 5.2.1. The share-space concept could offer the logistic benefits of the share-platform concept whilst having the flexibility to tow the wind energy structures to shore. Although the share-space strategy requires more crew transfers and is more difficult to install, it might offer a form of cooperation that requires less interaction between stakeholders and could thus be easer to realise.
- Related to the development of the preferred concept presented in chapter 6, it is recommended to study the trade-off between the dimensions of the wind energy platform and the sizing of the aquaculture module.

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Appendix A

Offshore aquaculture development licences

Table A.1 Overview of relevant development licence applications in Norway

Company name	Permits	MTB [tonnes]	Project Name	Type of project
Closed technology:				
Marad Norway	5	1560	Torus Seafarm	
Offshore / exposed technology:				
NRS and Aker	15	11700	Arctic Offshore Farming	Semi-submersible offshore fish farms
Ocean Aquafarms	16	10140	Hex Box	Semi-submersible
Mari Culture	16	12480	Smart Fishfarm	Semisubmersible
Viewpoint Seafarm Nova Sea	20	15600	Modular Seawater	
Erko Seafood	16	12480	North sea fish farm	
Nova Sea	4	3120	Spidercage	Closed offshore plant
Gigante offshore	9	7020	Offshoremerd	
Roxel	14	10920	Octopus	Semi-submersible
Offshore Salmon	7	5460		
Blom fish farming	6	4680	Ocean Globe	
Wilsgård Fish farming	1	8580	Offshore Tank Fleet	
Evne AS	10	7800	Wave Master	
Entail Farming	29	22620	Offshore fish cage	
Unitech Salmo Solar	4	3120		Floating plants on exposed sites.
Infotronic ANS	6	4680	Jacktell	Jack-up platform
Inocap / Subsea Farming	6	4680		
Marine Harvest Norway	36	28080	Aqua Storm	
Astafjorden Ocean Salmon	8	6240	Øymerd	Concrete structure

Appendix B

Functions, requirements and costs segmentation

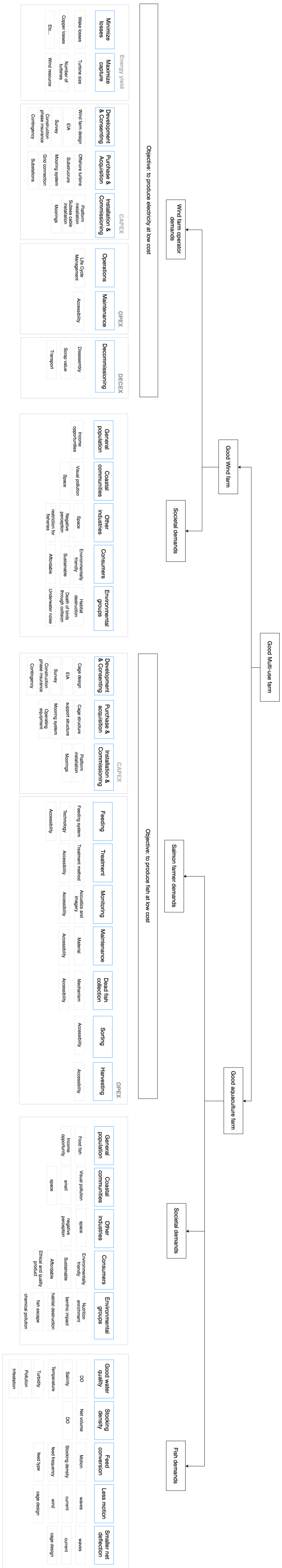


Fig. B.1 Important parameters from stakeholder perspective

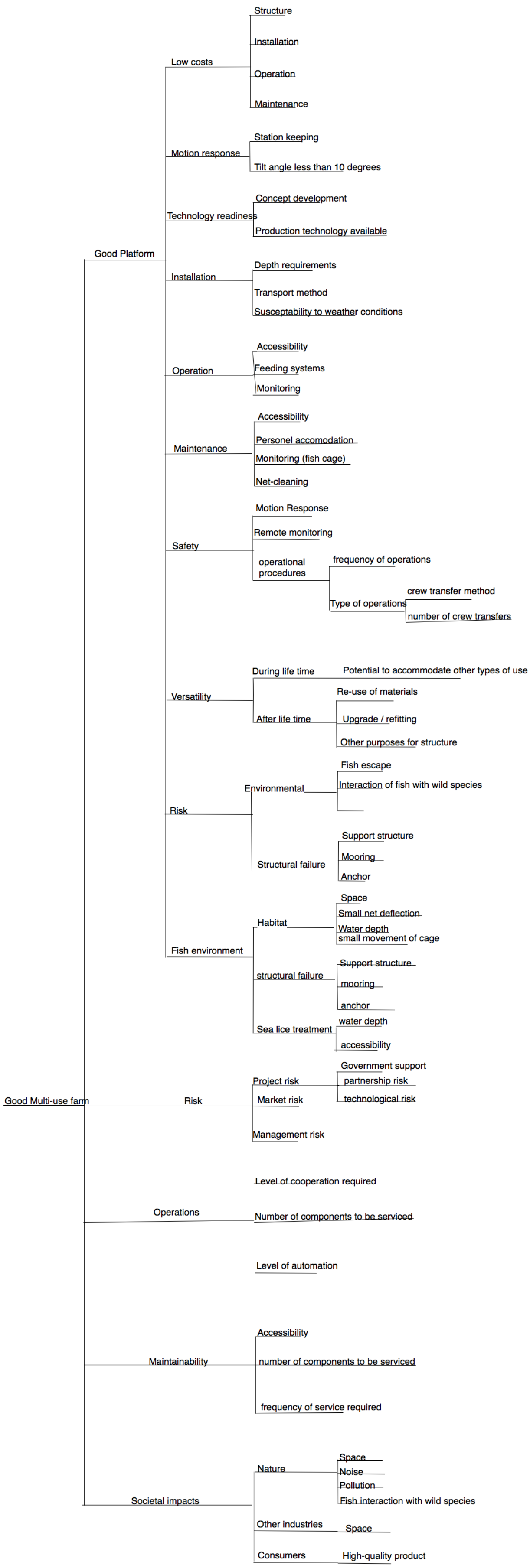


Fig. B.2 Tree with main objective from multi-use perspective

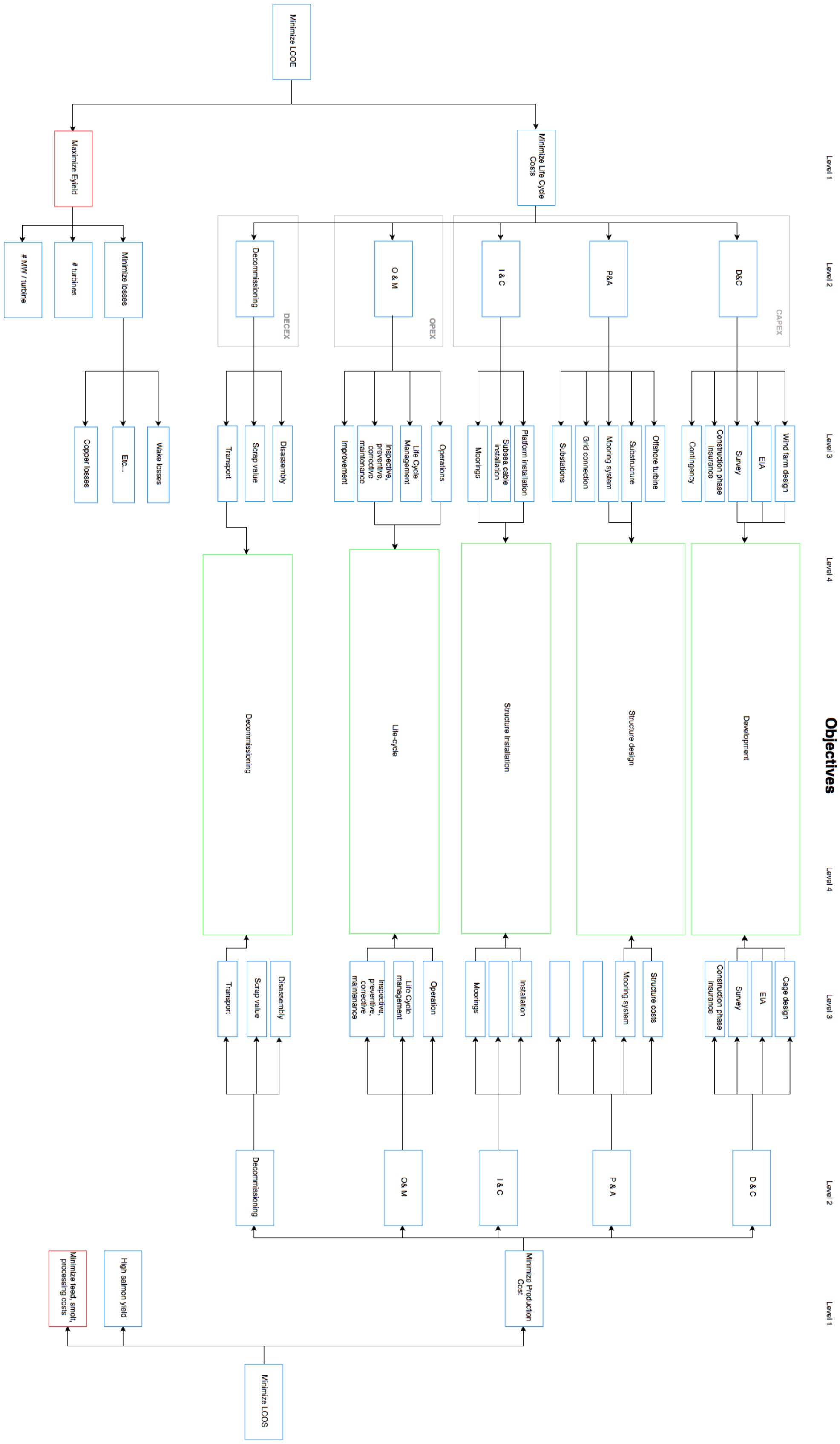


Fig. B.3 Tree from both wind energy and aquaculture perspective, targeted at finding common ground

Appendix C

List of experts

Table C.1 List of experts

Expert	Institution / Company	Area of expertise
Prof. Richard Langan	University of New Hampshire	Aquaculture
Dr. D. Fredriksson	U.S. Naval Academy	Aquaculture engineering
Dr. ir. M.B. Zaayer	Delft University of Technology	Wind energy
Niklas Hummel	Hexicon AB	Wind energy
Eduard Dyachuck	Hexicon AB	Wind energy
Christian Kosacki	MARINTEK	Closed cage aquaculture
Torbjørn Eggebø	Ocean Aquafarms	Offshore aquaculture
Clym Stock-Williams	ECN part of TNO	Wind energy O&M
Lucas Zaat	Damen Shipyards	Vessels - Product Design
Marije de Jong	Damen Shipyards	Aquaculture Vessels - Design & Proposal
Sebastian Sanchez	Delft University of Technology	Wind Energy
Hans Bjelland	EXPOSED centre	Offshore aquaculture

Appendix D

Inputs for stochastic sensitivity analysis

Methodology: Butler

Table D.1 Defining uncertainty in weight factors

Criterion	Distribution type	Range
All criteria	uniform	0-1

Methodology: Hyde

Table D.2 Defining uncertainty in weight factors from operator perspective.

Criterion	Baseline weight (mean)	Distribution type	Standard deviation	Range
CAPEX	8	normal	0.25	
Operability	3	uniform		2-4
Maintainability	3	uniform		2-4
Energy yield	9	uniform		8-10
Use of ocean space	1	normal	0.25	
Environment	3	uniform		2-4
Safety & health	1	uniform		0-2
Technology Readiness	2	normal	0.25	

Table D.3 Input: defining uncertainty in weight factors from society perspective. The baseline weight equals the score, which serves as mean for specification of the normal and uniform distribution.

Criterion	Baseline weight (mean)	Distribution type	Standard deviation	Range
CAPEX	5	normal	0.25	
Operability	3	uniform		2-4
Maintainability	3	uniform		2-4
Energy yield	3	uniform		2-4
Use of ocean space	9	normal	0.25	
Environment	10	uniform		9-10
Safety & health	9	uniform		8-10
Technology Readiness	1	normal	0.25	

Table D.4 Defining uncertainty in performance values.

Criterion	Distribution type	mean	standard deviation
All criteria	normal	S_{ij}	0.25

Appendix E

Aquaculture survey

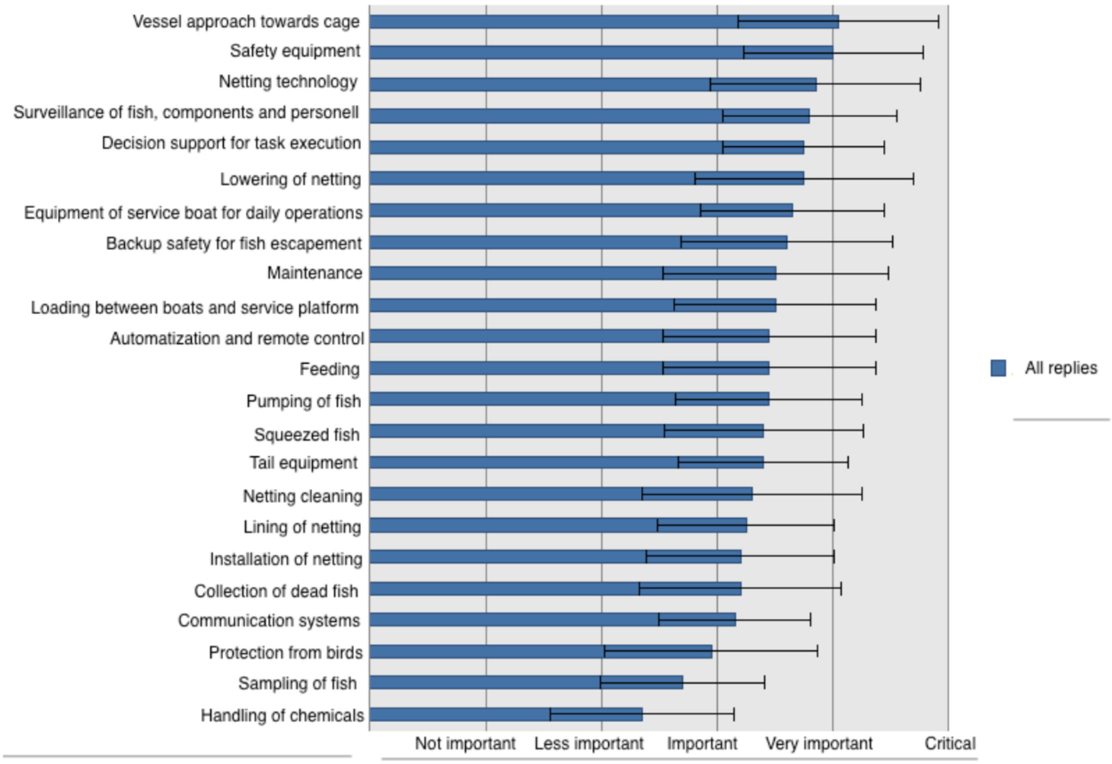


Fig. E.1 Aquaculture survey results reported by SINTEF [56]

Appendix F

Aquaculture vessels

UTILITY VESSEL

UV SERIES

DAMEN

TARGET MARKETS AND ACTIVITIES

- Oil, gas and renewables
  - Repair and maintenance
  - Hydrographical survey
  - Dive- and ROV support
- Navigation aids services
  - Buoy laying
  - Hydrographical survey
  - Lighthouse supply
- Aquaculture
  - Installation and removal works
  - Repair and maintenance
  - Delousing
- Environmental protection
  - Fire fighting
  - Oil recovery

The Utility Vessel Series offers owners a flexible offshore workboat solution for inshore and offshore operations.

TO SUPPORT THESE ACTIVITIES OUR UTILITY VESSELS SHARE THE SAME BASIC DESIGN FEATURES:

- Large clear deck areas.
- Cargo hold, stores and offices dedicated to project use.
- A large accommodation, not only for crew but also for project teams.
- A high level of comfort that will make seafarers and non-seafarers feel at home whilst at sea.

Further a wide selection of options is available to tailor your Utility Vessel to suit your requirements.

Our Utility Vessels embody Damen's exten
workboats and

◀ UV 2711
◀◀ UV 3711

The rule length of the UV 2711 is below 24m and the gross tonnage of the UV 3711 is below 500GT. Both can be fitted with all necessary equipment to support the aquaculture industry.

◀ **UV 5514**
This vessel offers an aft deck of 250sqm and a raised and protected project deck of 90sqm. This latter deck is ideally suited for a LARS, a second workboat or a compact access system.
A project office and project store are located adjacent to the work decks.
The accommodation has 7 single cabins and 20 double cabins. Two day rooms offer privacy for crew and boarding parties.

ADVANCED DESIGN
Propulsion and power generation systems are optimised per project for good fuel economy.
For this it is also essential to focus on the right hull form. The UV series therefore adopts the hull form as used for the Damen PSV series. This proven and efficient hull includes a bow design that reduces slamming which results in improved comfort and safety.

EQUIPMENT PACKAGES
- Diesel direct, diesel electric or hybrid propulsion packages
- Fixed shafts or rudder propellers
- Single, multiple or retractable bow thrusters
- Crane, A-frame and access system options
- Basic towing & anchor handling equipment
- Dynamic positioning, 4-point mooring
- And more…..

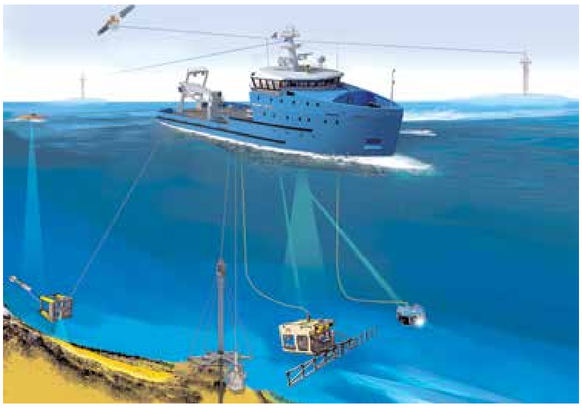
WORK-LIFE BALANCE
Special attention is given to living and working spaces onboard the vessels.
The accommodation is designed to the highest standards, and offers large mess/dayrooms and cabins with en-suite sanitary.
Well laid out service and machinery spaces ensure excellent workability and maintainability. All this adds to creating safety and comfort at sea.

sive global experience with a wide range of offshore vessels.

DAMEN

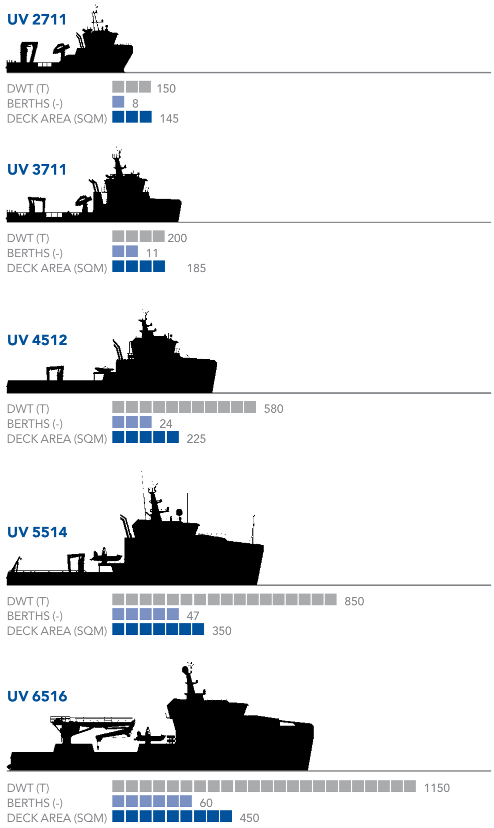
THROUGH-LIFE SUPPORT
At Damen we value the relationship with our customers and therefore we offer a wide-ranging portfolio of after sales services, covering the complete vessel's operational lifecycle. From start-up and warranty period through deployment to lifetime extension. We help our customers achieve their goals in terms of uptime, reliability and costs.

FINANCIAL SOLUTIONS
Our Customer Finance facilities are not just for privately owned, small and medium-sized companies. We also assist government bodies such as port authorities. Damen maintains relations with all Netherlands-based commercial banks, as well as with numerous banks abroad. As a major client of the Dutch Export Credit Agency, Atradius, Damen is highly experienced in arranging export loans with export credit insurance facilities.



DAMEN TECHNICAL COOPERATION (DTC)

DTC enables you to build your Utility Vessel locally, anywhere in the world. We provide you with a prefabricated shipbuilding kit and can, on request, combine this with expert assistance, training and back-up. By using standardised components it is possible to make a custom-built design, fulfilling the specific local requirements. One in every five Damen vessels are built on-site by DTC.



FOR THE LATEST INFORMATION ON THE UTILITY VESSEL SERIES VISIT DAMEN.COM

2015-02

UTILITY VESSEL SERIES

DAMEN

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Appendix G

Capital costs of net-pen salmon cage

Table G.1 Capital costs for a 3300 ONP net-pen in coastal area [43]

Items	Costs
Licences	€ 23.571.429
Floating rings	€ 1.834.286
Nets	€ 857.143
Moorings	€ 342.857
Boats	€1.285.714
Feed barges	€1.371.429
Camera systems	€ 214.286
Feed distributors	€ 34.114
Power systems	€ 188.571
Total	€ 29.699.829,00

Appendix H

Platform dimensions

Table H.1 Platform dimensions. (hub-hub) and (c-c) mean that the distance is measured between the centrelines of the columns of the platform and the hubs of the wind turbines respectively. (Source: Hexicon)

	Unit	2^{nd} gen. 20 MW	2^{nd} gen. 10 MW	Dounreay Trì 10 MW
Turbine spacing (hub-hub):	m	187	135	200
Platform length (c-c):	m	135	100	200
Platform beam (c-c):	m	65	48	100
Hub height:	m	110	-	-
Truss weight:	t	4130	-	-
Column weight:	t	2025	-	-
Tower weight:	t	2x 1020	-	-
Turbine weight:	t	2x 675	2 x 350	2 x 350
Total displacement:	t	20500	6750	12659
Draft	m	-	14	15
Total platform weight	t	-	2540	6180

Appendix I

Site classifications for aquaculture

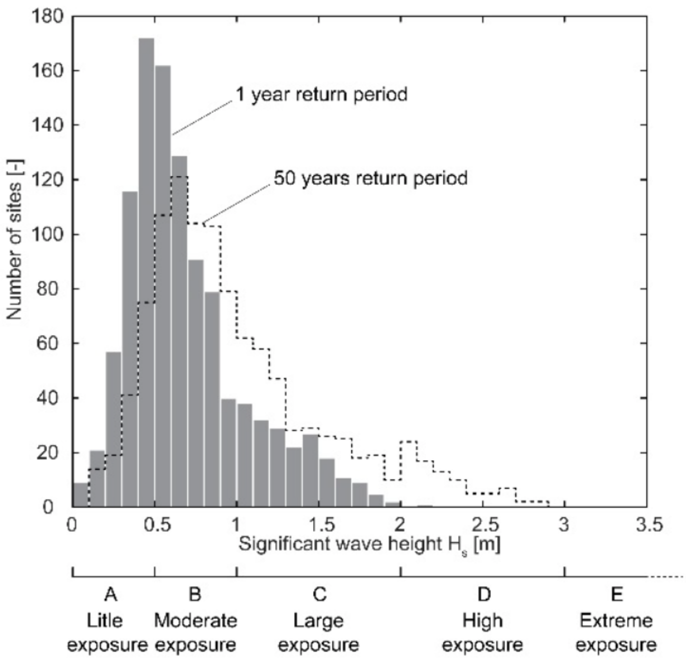

Fig. I.1 Distribution of significant wave height H_s for 1 and 50 years return period for all 1070 Norwegian salmon sites. The classification is taken from Norwegian Standard NS9415.

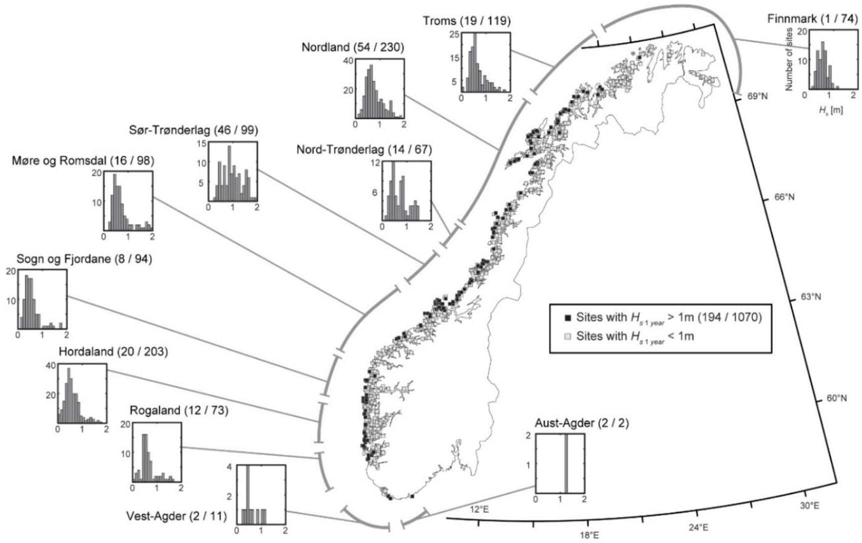

Fig. I.2 Distribution of H_s in each of the Norwegian counties. The number in parentheses show the number of sites with $H_{s\ 1year}$ larger than 1m compared to the total number of sites in the area. The sites with a $H_{s\ 1year}$ higher than 1m are shown as black squares, and illustrate the 'frontier' which offshore aquaculture is facing. [6]

Table I.1 Site classification for aquaculture practices based on current speed, according to Norwegian Standard NS 9415 [18]

Site class	Current speed[m/s]	Degree of exposure
a	< 0.3	Small
b	0.3 - 0.5	Moderate
c	0.5- 1.0	Medium
d	1.0 - 1.5	High
e	> 1.5	Extreme