Master's thesis

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Aluminium Concept Development of Sustainable and Modular Closed Fish Farm

Master's thesis in Mechanical Engineering
Supervisor: Geir Ringen
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Summary

The goal of this thesis is to explore the possibilities of a modular and scalable aluminium concept for a closed aquaculture system. The thesis aims to identify possible solutions through continuous concept development, literature studies, and cooperation and communication with leading experts and associated industry. This development project was conducted in cooperation with TechnipFMC and NTNU Aluminium Product Innovation Centre.

With set-based product development principles and rapid concept development, this thesis focuses on covering a wide range of research to identify the critical factors affecting the solution space. Visual CAD models of the different solutions and continuous communication with leading experts were key tools to ensure the progress of this project. The findings were validated by collaborating with a wide network of external contacts.

Literature studies were conducted to map the requirements, standards and regulations relevant to this project. The hydrodynamic loads of closed aquaculture systems, the utilization of aluminium in aquaculture applications, aluminium manufacturing, model scaling theory and modular product development theory are also presented in this thesis as the foundation of development.

During the project period, several concepts with a focus on modularity, scalability and the available manufacturing methods for aluminium were generated. Narrowing down the solution space by rejecting the least feasible ideas resulted in a concept based on friction stir welded panels with an external stiffening structure inspired by the shipbuilding and offshore industry. The resulting concept accommodates modularity and scalability, together with well-known manufacturing and assembly methods to minimize costs.

More research on the topic of hydrodynamic load combinations for closed aquaculture systems is required for further development on the thesis results. With the load scenario at hand, the structure dimensions can be determined and used to estimate the project costs. Whether or not aluminium is a competitive material to for example concrete and glass fiber-reinforced plastic for the closed fish farming industry can then be validated.

Sammendrag

Målet med denne oppgaven er å undersøke mulighetene for et modulært og skalerbart aluminiumkonsept for et lukket oppdrettsanlegg. Denne oppgaven tar sikte på å identifisere mulige løsninger gjennom kontinuerlig konseptutvikling, litteraturstudier, og samarbeid og kommunikasjon med ledende eksperter og tilknyttet industri. Dette utviklingsprosjektet ble gjennomført i samarbeid med TechnipFMC og NTNU Aluminium Product Innovation Center.

Med settbaserte produktutviklingsprinsipper og hurtig konseptutvikling fokuserer denne oppgaven på å dekke et bredt spekter av forskning for å identifisere de kritiske faktorene som påvirker løsningsrommet. Visuelle CAD modeller og kontinuerlig kommunikasjon med ledende eksperter var de viktigste verktøyene for å øke fremdriften i prosjektet, sammen med et bredt nettverk av eksterne kontakter for å validere funnene.

Litteraturstudier ble utført for å kartlegge kravene, standarder og forskrifter som er relevante for dette prosjektet. Den hydrodynamiske belastningen på lukkede oppdrettsanlegg, bruken av aluminium i oppdrett, aluminiumproduksjon, modellskaleringsteori og modulær produktutviklingsteori presenteres i denne oppgaven som grunnlag for utvikling.

I løpet av prosjektperioden ble det utviklet flere konsepter med fokus på modularitet, skalerbarhet og tilgjengelige produksjonsmetoder for aluminium. Å innskrenke løsningsrommet ved å forkaste de minst gjennomførbare ideene resulterte i et konsept basert på FSW-paneler med en ytre avstivningsstruktur inspirert av skipsbygging og offshore industri. Det resulterende konseptet er tilpasset modularitet og skalerbarhet, sammen med kjente produksjons- og monteringsmetoder for å minimere kostnadene.

Mer forskning innen hydrodynamiske lastkombinasjoner for lukkede oppdrettsanlegg er nødvendig for videreutvikling av konseptene. Med lasttilfellet tilgjengelig kan konstruksjonsdimensjonene bestemmes og brukes til å estimere prosjektkostnadene. Hvorvidt aluminium er et konkurransedyktig materiale sammenlignet med for eksempel betong og glassfiberarmert plast for den lukkede oppdrettsindustrien, kan da bli validert.

Acknowledgements

We would like to thank our research supervisor - the Head of NTNU Aluminium Product Innovation Centre, Geir Ringen for his invaluable engagement and guidance throughout this project. Further, we would like to thank Engineering Specialist Tore J. Høgberget and Project Manager Runar Halvorsen from TechnipFMC, as well as their colleagues, for their close collaboration and contributions.

We would also like to thank Hydro, Marine Aluminium, SINTEF Ocean, SINTEF Manufacturing and Kapp Aluminium for their technical and knowledgeable guidance. A special thanks to Hydro Aluminium Magnor for letting us attend at the informative and interesting Hydro Profile Academy 2018.

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Abbreviations

BSL	=	Below sea level
CAD	=	Computer aided design
CNC	=	Computer numerical control
DNV	=	Det Norske Veritas
DNV-GL	=	Det Norske Veritas Germanischer Lloyd
FSW	=	Friction stir welding
DFM	=	Design for manufacturing
DFX	=	Design for X
GRP	=	Glass-reinforced plastic
HAZ	=	Heat-affected zone
MAB	=	Maximum allowed biomass
MIG	=	Metal inert gas welding
NAPIC	=	NTNU Aluminium Product Innovation Centre
NFSA	=	Norwegian Food Safety Authority
NS	=	Norwegian Standard
NTNU	=	Norwegian Uneversity of Technology and Science
N/A	=	Not applicable
R&D	=	Research & development
SBCE	=	Set-Based Concurrent Engineering
SE	=	Southeast
SW	=	Southwest
TIG	=	Tungsten inert gas welding
W	=	West
WFE	=	Whole fish equivalent

Symbols

a	=	coefficient of linear thermal expansion
C	=	force coefficient
δ	=	deflection
δ_F	=	deflection of full scale
δ_M	=	deflection of model
E	=	modulus of elasticity
F_g	=	gravitational force
F_i	=	inertia force
$f_{m,n}$	=	wave responses
F_n	=	Froude number
F_v	=	viscous force
G	=	shear modulus
g	=	gravitational acceleration
H_s	=	significant wave height
I	=	second moment of inertia
L	=	physical length
L_F	=	dimension of full scale
L_M	=	dimension of model
λ	=	length scale constant
ν	=	Poissons's ratio
μ	=	fluid viscosity
Re	=	Reynolds number
ρ	=	density
T	=	wave period
T_p	=	peak wave period

U	=	velocity
U$_F$	=	velocity of full scale
U$_M$	=	velocity of model
v$_{b,o}$	=	fundamental wind velocity value
v$_c$	=	mid-current
v$_m$	=	mean wind velocity

Chapter 1

Introduction

1.1 Background and Motivation

The Norwegian aquaculture industry has experienced rapid growth since the establishment of the first salmon fish cage at Hitra in 1970 [53]. In 2017, Norway produced 1.350 million tonnes WFE salmon and earned 94.5 billion NOK from export [39]. As a result of the expanding industry, farming practices are increasingly focused on by R&D companies, biologists, and especially politicians and consumers who demand promotion of fish welfare. The industry is forced to better monitor their production and ensure fish welfare throughout the whole life cycle [13]. This is challenging due to the problems with salmon lice and the desire to better control the production to promote good living conditions and growth. Also, the increased amount of development licenses available in Norway the previous years contributes to involvement from new firms and competitors [32].

As the aquaculture industry in Norway aims to modernize their strategy and operations to increase both fish welfare and growth, the traditional net pen is challenged by the closed cage system. Numerous closed cage designs are developed and tested. Nevertheless, the technology is young and permits further customization and development the next years.

1.2 Objectives

Through NTNU Aluminium Product Innovation Center (NAPIC) and in collaboration with the oil and gas company TechnipFMC, a pre-study and this master project is executed to investigate the topic of aluminium concept development of sustainable and modular closed fish farms. The main purpose of this thesis is to gather theory and experience from the affected industry, and utilize product development methodologies to develop a foundation for later exploration and development of modern, closed fish cage systems.

1.2.1 Research Objectives

- Explore a development methodology suitable to discover the solution space of sustainable and modular closed fish farm concepts in aluminium.
- Evaluate and adjust the method of work to continuously enhance the development progress and the investigation of the solution space.
- Demonstrate and validate the possibility of introducing aluminium as a new, sustainable and reliable building material to the fish farming industry.

This project shall be carried out with a focus on mapping the solution space through a broad literature study and knowledge gathering from dialogue with external experts and experienced companies. The resulting paper shall serve as a thorough knowledge base for further development and engineering in TechnipFMC.

A structured set-based product development methodology shall be implemented to organize and guide the development process of this paper. Well known methodologies shall be investigated to gather inspiration for a structured work method suitable for us, satisfying task 9 from Section 1.2.2. Slight adjustments and change in practices are expected for the well known methodologies to be appropriate to a two-person team investigating a complex industry. Changes should be specified and evaluated throughout the project.

As no known closed fish farms with aluminium as the main construction material exists, the project also aims to explore the possibility of introducing a new material alternative to the industry. This includes studies of aluminium structures in marine application and appropriate design decisions for low-cost manufacturing.

1.2.2 Tasks

In order to achieve the outlined research objectives, the following tasks shall be accomplished and presented in this thesis:

1. A description of the classifications of fish farming systems.
2. An overview of the main functions of a closed aquaculture system.
3. A literature study regarding relevant requirements, standards and regulations.
4. A literature study regarding hydrodynamic forces.
5. A literature study regarding aluminium in marine applications.
6. A literature study regarding aluminium manufacturing methods.
7. An introduction to model scale testing.
8. An introduction to modular product development.
9. Implement a structured approach for concept generation.
10. Generate and develop a closed fish farming concept in aluminium based on the most reliable findings.

1.3 Project Scope and Report Structure

The following sections outline the scope and work carried out as part of this master thesis including the work performed to increase the reliability of the document, limiting factors, report structure and finally a list of all collaborators and sought out experts.

1.3.1 Actions Performed to Ensure Reliability

A series of actions were carried out in order to increase the reliability and further use of this thesis. The literature studies and theoretical understanding were obtained through conversation with accredited researchers and employees within the field, or from a broad collection of peer-reviewed academic papers. A large fraction of the expertise utilized in this project is located in Norway. To decrease any bias this would introduce, great care was taken to include written papers and documentation from other countries and research environments. As the study was performed in collaboration with employees from TechnipFMC located in Norway, the Norwegian requirements and standards for construction and fish farming were the prevailing regulations. Further, by keeping transparency within the project, the relevance of all findings was shared and reviewed. All information found essential in order to create a foundation for further and more thorough development is presented in this paper.

1.3.2 Literature Study

Presented in Chapter 2 are the findings from the literature studies commenced in August 2018 as part of the pre-study and supplementary theory found essential during the thesis work. The sub-sections based on findings from the pre-study paper: "Aluminium Concept Development for Sustainable and Modular Closed Fish Farm" [28], will be specified.

Chapter 2 is a comprehensive segment that includes point 1-8 listed in Section 1.2.2. The outlined tasks represent the assumed core of influencing factors and elements that affect the concept development and require further insight. To cover a wide knowledge area, the literature study was divided into different focus areas in the pre-study and master project period. This was done to quickly gain a grasp of the most critical factors, before conducting deeper research on the relevant topics. Continuous communication and collaboration within the team and with external collaborators was found necessary to identify the focus areas and influencing factors presented in this thesis.

1.3.3 Concept Generation

The Set-Based Concurrent Engineering (SBCE) and the Design for X (DFX) methodologies were implemented as inspiration for the work method in this project, satisfying task 9 from Section 1.2.2, and is described further in Section 1.4. The concept generation phase focused on continuous communication and reviewing of the progress in collaboration with the stakeholders and other involved contributors. The methods implemented in the development phases and the primary outcome are further described and illustrated in Chapter 3. Finally, Chapter 3 presents the solution sets investigated and recommended production methods generated in corporation with employees from TechnipFMC, Hydro, Marine Aluminium and other contacts. The final concept iteration aims to achieve task 10 from Section 1.2.2.

1.3.4 Discussion and Conclusion

Chapter 4 and 5 contains the discussion and the finishing conclusion of this thesis. The discussion includes a review of the implemented development methods, the literature studies, the concept development, the final concept iteration, and the collaboration and validation of this project. As the resources available and the limited time frame have defined the scope of this project, a recommendation for further work is implemented in the final chapter of this paper.

1.3.5 Limiting Factors

The collected theory and concept generation presented in this thesis are based on the work performed by our small two-person team during the spring 2019 and findings in the pre-study fall 2018 [28]. The scope of the research objectives and outlined tasks are meant to reflect our limited resources and time frame. The requirements and requests provided by our collaborator TechnipFMC in advance and during the project have affected which topics to bring into focus. To compensate for our lacking experience within the fish farming industry and complex structural development in aluminium, a broad network of experienced contacts are sought out to validate the findings.

1.3.6 Collaborators and Other Contacts

This project was conducted in close collaboration with employees at TechnipFMC, including weekly status meetings and two gatherings in Trondheim. The weekly meetings enabled discussions about progress and further work in addition to facilitating continuous feedback and transfer of knowledge. Supplementary meetings with employees at SINTEF Ocean and the Department of Marine Technology

NTNU where conducted to acquire additional perspective on the project scope and chosen focus area. Table 1.1 summarizes the main contact persons and their contributions. Visiting Hydro Aluminium Magnor and participation at the Hydro Profile Academy promoted the understanding of aluminium construction and manufacturing, while cooperating on design improvements with both Hydro and Marine Aluminium employees improved the outcome of the performed work.

It was also attempted to organize a visit to a functioning closed fish farm at the Norwegian Aquaculture Center, but this proved difficult in the time span available. Visiting and learning from a functioning closed fish farm could be beneficial to get a better understanding of the industry.

Table 1.1: Overview of contact persons throughout the project.

Name	Company	Role	Contribution
Geir Ringen	NTNU NAPIC	Main supervisor	Feedback and supervision throughout the project.
Tore J. Høgberget	TechnipFMC	Main contact person	Continuous dialog throughout the project. Contributed to development and progress.
Sven Haagenes Høy	TechnipFMC	Technical recourse	Resource on technical development and solutions.
Runar Halvorsen	TechnipFMC	Technical recourse	Resource on technical development and solutions.
Lars Stian Johansen	TechnipFMC/ Edelfarm	Biolog	Fish welfare.
Björn Burgmann	NTNU	Theoretical recourse	Set-based concurrent engineering methodlogy.
Christer Westum Elverum	NTNU	Supervisor	Contact point and source of knowledge.
Otto Lunder	NTNU	Material recourse	Aluminium in marine environments.
Pål Lader	NTNU	Contact person	Marine constructions and future prototype tests.
Thomas Svendsen	Hydro	Technical recourse	Design development and production costs.
Göran Olsson	Hydro	Technical recourse	Design development and production costs.
Anders Helander	Hydro	Technical recourse	Design development and production costs.
Leif M. Kaalaas	Marine Aluminium	Technical recourse	Design development and evaluation.
Ole Terje Midling	Marine Aluminium	Technical recourse	Design development and evaluation.
David Kristiansen	SINTEF Ocean	Technical recourse	Sea characteristics of closed fish farm structures.
Tore Tryland	SINTEF Manufacturing	Technical recourse	Aluminium constructions.

1.4 Development Methodology

Closed containment aquaculture is new technology which still undergoes research and development by the industry [61]. Because of both the early phase of the technology and the competition in the market, information on how to construct closed aquaculture pens is not readily available. As a consequence of this, the development of a closed aluminium aquaculture structure becomes highly dependent on the gathering of information and research. In our case with a small development team, the gathering of information and research was reliant on communication with the industry and other leading experts. Implementation of a structured development methodology was important to effectively gather information, communicate ideas and generate concepts.

A development methodology is an approach to perform product development; how to structure the development team, manage the time-frame, communicate, and measure progress. Different methods are used by different companies and for different applications. The common goals of these development methodologies are to increase the efficiency of development, and minimize the time spent making mistakes and correcting them. In the early stage of concept development it is important to be aware of the risk of making mistakes and how the development progress will affect the final product. The initial concepts are the foundation for further development and can determine the feasibility of the project. Implementing structured approaches for concept generation and concept selection reduces the risk of running into problems which could have been avoided.

It is reported that 60-75% of the life cycle costs of a project are determined by decisions done in the concept phase, and up to 85% before detailed design starts [36]. This highlights the importance of assurance and verification throughout the concept development phase. This thesis will not go beyond the concept development phase and into detailed design, but focus on exploring several solution sets, and creating a solid foundation for further development. By focusing on gathering information and identifying a feasible design domain, this thesis enables TechnipFMC to decide on further development with greater confidence.

To optimize and structure the work method of this paper, two well known development frame works are further explored. This in accordance with the outlined research objective presented in Section 1.2.1. The development methodology utilized in this project gather inspiration from SBCE described by Sobek et. al. in "Toyota's Principles of Set-Based Concurrent Engineering" [54], with focus on front-loading, exploring solutions and visual communication. Burgmann at NTNU was contacted to further discuss the methodology and point out relevant articles on the theory. Another mindset explored in this project was the DFX methodology with main focus on manufacturing. This methodology guides the concept development to exploit the advantages of aluminium manufacturing.

These methodologies are both commonly utilized by large development teams in the industry to solve various development issues. In our case, the thesis work aims to explore how these methodologies can be implemented in an early concept development project for a small, independent development team working on a large and complex system. The next sections introduce the main principles of the SBCE and DFX and how these are implemented in our project.

1.4.1 Set-Based Concurrent Engineering

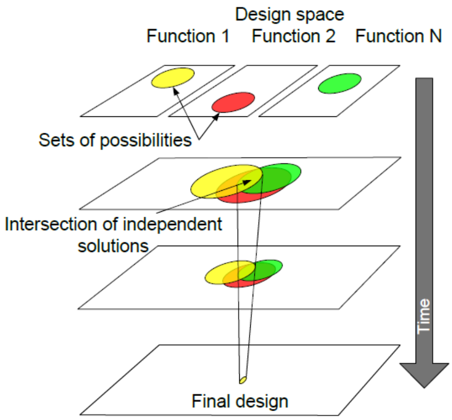
The approach of Set-Based Concurrent Engineering is characterized as a process of developing multiple sets of solutions in parallel. It differs from the traditional development methodology which is distinguished by an early selection of one identified solution as basis for further refinements [45]. SBCE also stands out on it's method of narrowing down the solution space; unfeasible solutions are gradually eliminated while several sets of possibilities for each sub-system is explored. This allows delay of decisions and design selections to remain open until an adequate amount of knowledge exists [68]. This method of exploring broader sets of possible solutions can seem more time consuming early on, but as more knowledge and experience are gathered it will converge quicker to a feasible solution [36].

Figure 1.1 illustrates the three principles of SBCE as described by Sobek et. al. [54]:

1. Map the design space.
   Define feasible regions, design multiple alternatives to explore trade-offs and communicate sets of possibilities.

2. Integrate by intersection.
   Look for intersections of feasible sets, impose minimum constraint and seek conceptual robustness.

3. Establish feasibility before commitment.
   Narrow sets gradually while increasing detail, stay within sets once committed and control by managing uncertainty at process gates.



[44]

Figure 1.1: Principles of Set-Based Concurrent Engineering.

In Toyota's SBCE methodology they focus on an early mapping of the design space. Understanding the possibilities and requirements for the product, and the technology available, generates a design space to work within. The constrains of the design space are based on what each development department deems feasible, based on their experience and earlier development projects. The solution that works best for the design department, may not work at all for the manufacturing department. Once different departments (e.g. design, manufacturing, assembly, logistics) map the possibilities and limitations of their design space, intersections of feasible sets be can found. To achieve this, continuous communication is necessary.

Once the feasible design space is mapped, exploration within this domain can start. By investigating multiple alternatives, exploring trade-offs and communicating the possibilities, the process assures the feasibility of the solutions. An important factor in exploring several alternatives is to not constrain the project unnecessary. Locking down specifications early can prohibit the optimization of the solution. It is viewed better to impose just enough constrains, in order to allow for adjustment and optimization. [54]

As multiple design alternatives are explored in parallel, the developers at Toyota focuses on understanding the possibilities and consequences of their design choices before implementing them. During the development phase the solution sets will narrow down as the least promising solutions get discarded, while the most promising solutions are developed further. As each design decision is researched, visualized and communicated thoroughly, the developers are able to establish the feasibility of their solution before committing to it.

Implementation in This Project

In this project, the mapping of the design space was a large part of the work, as no prior experience or earlier development projects on the topic of *closed fish farms in aluminium* was available at the time of writing. This meaning that front-loading of the resources by allocating a large amount of time to research and gather information early in the project was crucial. As there existed no other development department in this project, communication with leading experts and the industry needed to be prioritized. To enable efficient communication with several different experts and the industry, visual communication was utilized as the most important tool in this project. By focusing on continuous rapid prototyping with hand sketches and CAD models, we were able to quickly communicate ideas and concepts, thus identifying intersections of feasible sets. With the digital models, we were able to quickly implement changes which made it possible to map the possibilities and challenges of this project.

The requirements determined by TechnipFMC, and an overview of the Norwegian standards and regulations, presented in Section 2.3, serve as a base guideline for the design domain in this thesis. It was better to view the standards and regulations as a design domain to work within, than viewing it as limiting factors to promote a positive mind-set.

Floating structures at sea are exposed to cyclic loads, and often stronger storms. Senior researcher at SINTEF Ocean Kristiansen was here consulted on sea characteristics of closed floating structures to facilitate a proper understanding of the subject.

As the marine environment is a highly corrosive environment, the application of aluminium needed to be thoroughly understood to ensure a satisfying lifetime of the final solution. There was no direct experience to be obtained from other aquaculture structures since there exists no other pens in aluminium, however, inspiration from solutions within other marine sectors and development projects have been relevant. Collecting inspiration from other industries, and possibly using existing components saves time and money which can be allocated to solving other critical sub-tasks.

To gain a better understanding of how to design and develop an aluminium structure, and how to make it modular and scalable, we attended the Hydro Profile Academy 2018 and visited the aluminium constructor Marine Aluminium. Further cooperation with Hydro was done to better understand the design choices and their consequences regarding cost, production and structural strength. Understanding the possibilities and limitations of aluminium component production was essential in the initial development phase to avoid costly or unachievable designs.

These actions and the research conducted were done to best possibly establish feasibility of the concepts developed in this project. Because this project was conducted in the early concept development phase, with focus on wide exploration, the only commitment done was to either discard a less promising solution or bring a promising solution along further in the development. Further establishment of feasibility must be conducted for later development stages.

1.4.2 Design for X

This section will introduce the Design for X methodology presented by Ulrich and Eppinger in the book "Product Design and Development" [64], and discuss how this mindset for product development was implemented in this project.

DFX is a common development methodology where the development team focuses on a specific aspect such as reliability, environmental impact, weight or manufacturability. These aspects are often directly related to customer needs and can be used to guide early concept development and determine decisions in later development. Design for manufacturing (DFM) is the most common of these methodologies because it directly affects the project costs. Manufacturing cost is often the key determinant when aiming to make a product economically sustainable. Especially when considering aluminium which is more expensive than the other common construction materials as steel, concrete and GRP; the cost of manufacturing needs to be minimized. The goal of DFM is to minimize manufacturing cost without sacrificing product quality. [64]

DFM requires a high level of communication and interaction between the development team and outside experts. Sketches, drawings and product specifications are utilized between the developers and outside experts to decide on design alternatives. The outside experts, manufacturing engineers and production personnel have a detailed understanding of production and assembly processes and are quickly able to point out design flaws. Companies often use structured, team-based workshops between developers and experts to map the feasible solutions. [64]

The majority of a products functions and characteristics are determined by the choices taken in the concept development phase. These decisions will therefore highly affect the cost, making it important to implement a DFM mindset early in the development. Cost estimates are however difficult to perform early in the project, but rough estimates can be used to guide design trade-offs. Concept trade-offs are done in most development processes, where one desired aspect must be sacrificed for another, these trade-offs are often based on cost estimates. Take weight reduction as an example: A reduction in weight will reduce material cost and make transportation easier, but can increase the manufacturing cost to surpass both.

Manufacturing costs often become a decision driver later in the development, in the detail-design-phase, but implementing it early on reduces the chance of late major changes in project. Cost estimates are difficult to perform in the concept phase because of the high level of uncertainty and the fast changing specifications. The methods to reduce manufacturing cost however can, and should still be introduced in this phase.

The main principles of reducing manufacturing cost are [64]:

- Reduce the cost of components.
- Reduce the cost of assembly.
- Reduce the cost of supporting production.
- Consider the consequences.

Implementation in This Project

Reducing the cost of components requires detailed knowledge of production methods and knowledge of which components that are easily available. Standard parts which can be sourced from suppliers will be significantly cheaper than getting custom-made parts. In this project communication with part manufacturers was essential. One of the worlds largest producer of aluminium, Hydro, was in this project consulted on both component manufacturing and design choices.

Reducing the cost of assembly involves minimizing the amount of labour required and the equipment/tooling needed. Designing for assembly is in its own a common design methodology, and focuses on facilitating assembly, making it easy, repeatable and cost efficient. How the product is assembled needs to be considered when designing, it does not matter how great a product is if it cannot be built. To bring in expertise on assembly, Marine Aluminium were consulted. Marine Aluminium is a Norwegian company which constructs aluminium structures for offshore use.

Reducing the cost of supporting production is often achieved through the first two points. Utilizing available, standard components reduces the need for large inventories as the parts can be ordered as needed, the same goes for reducing the number of parts to facilitate assembly. Easier assembly reduces the number of workers needed, and by that the need of supervisors and human resource management. Standardized parts reduce the need of engineering support and quality control.

Finally, considering the consequences of choices done to reduce cost are important as most choices are trade offs. If the choices to reduce cost affects the quality of the product, or interferes with the customer requirements the cost reduction will not matter because the product cannot be sold.

DFM serves as an important tool when developing a concept for an aluminium structure because it allows the full potential of aluminium manufacturing to be utilized. Compared to steel, aluminium does not have the same stiffness properties, and more material might be needed to achieve the required structural stiffness. Aluminium however has a great advantage in manufacturability and recycling, and this must be exploited to reduce the manufacturing cost and create an economical sustainable concept. Theory on the topic of aluminium manufacturing is presented in Section 2.6, and how the mindset of DFM inspired the development and the feasibility of the solutions investigated are further described in Chapter 3.

1.4.3 Concept Development

A concept is a description of the technology, working principles and form of a product. Concept generation is inexpensive, and can be done very quickly. A good final concept should create confidence that all other alternatives have been explored, and the best one is selected for further development. Accomplishing this requires thoroughly researching as much as possible in the early stages of development, creating several concepts and communicating ideas.

Figure 1.2 illustrates the iterative concept development method utilized in this project. During the research phases, there were focus on extracting new knowledge and maintaining continuous concept generation. By utilizing visual tools, creating concepts and communicating them to the customer, new important questions and problems were discovered throughout the early concept phase. The weekly status meetings focused on updating TechnipFMC on the progress, discussing concept ideas, receiving feedback, new information, and new design requests. Collection of new information can often trigger the emergence of new requests and design requirements. Continuously reviewing the requirements contributed to the creation of a better end product, and less waste on rework on undesirable concepts. By visualizing and communicating different approaches and results it is easier to identify promising solutions, discard those who are not and expose areas where more research is required.

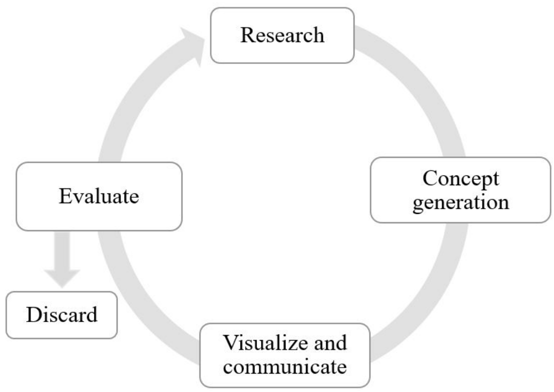


Figure 1.2: Iterative development process.

Chapter 2

Literature Studies

Developing a structure for the farming of fish under controlled conditions require knowledge not only of structural design and manufacturing, but also a great understanding of the biological aspects of the industry. Theory is gathered and presented in this chapter to increase awareness of the different aspects of fish farming.

Starting with a brief introduction in Section 2.1 of the classification of fish farming systems to define the basic terms used in this thesis, then in Section 2.2 are the main functions and advantages of a closed aquaculture system compared to the traditional net pen presented. Afterwards, in Section 2.3, follows a recapitulation of the requirements, standards and regulations affecting the solution space of this project and Section 2.4 elaborates on the theory of hydrodynamic loads.

To understand the opportunities within aluminium construction and manufacturing, the theory on these topics were studied thoroughly and presented in Section 2.5-2.6. This sections also include aluminium in marine applications and relevant joining techniques. When the concept development phase reached a specific point, the need for model testing increased to maintain progress and learnings. The issues and requirements connected to scaling are presented in Section 2.7. The final section of this chapter, Section 2.8, outlines the characteristics and motivation of modular product development theory to clarify its significance in this project.

2.1 Classification of Fish Farming Systems

This classification section is based on the research done in the pre-study [28]. There are two main types of fish farming systems based on a hydrodynamic perspective; either an open system or a closed system. An open system refers to farming cages in natural water surroundings, like the traditional net pen. The water volume is here allowed to move freely through the enclosed volume, following the natural currents at the location. In opposition are the systems that fully separates the internal water volume from the surroundings. These are classified as closed systems and includes a watertight pen. A closed system offer the opportunity to control the water quality and internal flow to obtain optimal conditions for the fish. [47]

This thesis concerns the development of a closed fish farming system. The closed systems are divided into subgroups based on their stiffness properties, similar to the definition in *SJØFLO* [32]. The stiffness properties are assumed critical to the behaviour of the fish farm when exposed to external forces such as environmental loads. The subcategories are:

- Stiff fish farm: No remarkable deformations while exposed to external environmental forces. Typically made of steel or concrete.
- Elastic fish farm: Noticeable elastic deformations while exposed to external environmental forces. Typically made of glass-reinforced plastic (GRP).
- Flexible bag fish farm: Remarkable deformations while exposed to external loads. Shape and behaviour are dependant of internal volume content.

2.2 Main Functions

As described in the previous section, a closed fish farm offers the opportunity to control the water quality and obtain optimal conditions for the fish. This is just one of several main functions of a closed aquaculture system. Closed aquaculture systems are significantly more advanced than open net pens, and an understanding of the system as a whole and awareness of its main functions are one of the first steps in a successful development project. This section will present the main functions of a closed aquaculture system as described in Teknologirådet's report on the future of salmon farming [61]. Characteristic details of the closed aquaculture system developed in this project will not be revealed, as this system is under development by TechnipFMC, and not available to the public.

According to Teknologirådet's report on the future of salmon farming, the main functions of a closed aquaculture system are [61]:

1. Prevent the escape of fish.
2. Prevent the spread of fish lice.
3. Prevent the spread of diseases.
4. Gather waste and prevent waste emissions.
5. Optimize growth and reduce food wastage.

A closed physical barrier will directly affect and satisfy the first main function listed above, and prevent direct contact with fish lice in the sea. Function 2-4, however, require the implementation of water and waste management, and would not be possible without the physical barrier. The possibility to control the water conditions and waste emissions often are the most central arguments for closed aquaculture systems. By collecting water from approximately 20-25m depth, a depth where there is little to no fish lice, the system can secure water collection without fish lice [61].

Treatment of the collected water can prevent diseases and control the spread. At the time of writing, the northern Norwegian coast was affected by the poisonous algae *Chrysochromulina*, reportedly killing approximately 7.8 million fish. That equals around 2.1 billion NOK in lost revenue [3]. This highly affects fish welfare as well, as wild fish are able to swim away from the poisonous algae, while fish in net pens are not. In the future, this can be prevented with closed fish farms, by control and treatment of the collected water for internal use.

A central argument to develop a closed system is the control of waste emissions. In traditional net pens, all the generated waste is emitted directly to the environment. A closed barrier allows for the collection and treatment of this waste, reducing local environmental impact and possibly generating a by-product for further processing and use.

Monitoring the water quality and the need for feeding enables function 5 and allows the system to create optimized living conditions for fish growth. The previous listed main functions of closed aquaculture systems promote more stable fish farming conditions, optimized growth, less disease, minimal fish lice, and minimal emission to the surrounding environment. These main functions of closed fish farms generate a need for additional infrastructure and control systems. Water circulation, treatment of the collected water, and waste collection all require piping and pump systems. In addition to this, the fish requires a current to swim against, generating a need for an internal artificial current [61]. All these systems need control and monitoring systems, and power supply. The required infrastructure will be described further in Section 3.2 as it is implemented in the concept development.

2.3 Requirements, Standards and Regulations

The fish farming industry is regulated through several governmental regulations and standards to ensure minimal hazardous events and improve fish welfare in all life stages. The contributors to the development of fish farms are listed in Section 2.3.2 and further described in Sections 2.3.3-2.3.8. In addition, the scope of this thesis is founded on a set of stakeholder requirements as presented in the following section. The requirements, standards and regulations in this section are based on the findings in the pre-study [28].

2.3.1 Stakeholder Requirements

The following list of stakeholder requirements is based on the project description and later communication with TechnipFMC employees. From the outlined requirements, the initial design room is indicated for further investigation and discoveries of possible solution alternatives. The requirements outline not only the goals of this thesis, but also further work by the employees in TechnipFMC. The syntax of the requirements are in accordance with the format outlined in the book "Systems engineering: design principles and models" [34].

The stakeholder requirements are as specified in the project assignment [28]:

1 The final design solution shall be scalable to meet the size limitations of a larger customer segment.

2 The final design solution shall be modular to simplify the assembly process.

3 The final design solution shall be sustainable in order to accommodate the environmental requirements.

4 The dimensions of the final design shall be approximately 30m diameter and 15m deep.

5 The dimensions of the designed modules should qualify for land based transportation.

6 The final product shall be self-bearing in the predetermined location given by the stakeholder.

7 The final product shall include a fish sorting mechanism designed and developed by TechnipFMC.

8 The final design solution shall account for the applied internal flow of the aquaculture water.

9 The implemented material shall be surface treated to minimize growth of algae and other species.

10 A literature study shall be performed to compare pros and cons of implementation of aluminium as the main construction material.

2.3.2 System Requirements

Several governmental regulations and standards affect the feasibility region of this design project. The regulations and standards that include influencing requirements are acquired from www.lovdata.no and www.standard.no and presented in Table 2.1 [35][55]. The main requirements are listed in the following sections to highlight the attributes and functions that the final solution must achieve to be realizable. Be aware of new versions of the regulations that surpass this recapitulated version.

Table 2.1: Regulations and standards affecting the project.

No.	Identity	Title
/001/	LOV-2009-06-19-97	Lov om dyrevelferd
/002a/	FOR-2008-06-17-822	Forskrift om drift av akvakulturanlegg
/002b/	FOR-2018-04-19-673	Forskrift om endring i forskrift om drift av akvakulturanlegg
/003/	FOR-2014-12-15-1831	Forskrift om fangstbasert akvakultur
/004/	NS-EN 1999-1-1:2007 + A1:2009 + NA:2009	Eurocode 9: Design of aluminium structures Part 1-1: General structural rules
/005/	NS 9410:2016	Environmental monitoring of benthic impact from marine fish farms
/006/	NS 9415.E:2009	Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation
/007/	NORSOK M-501	Surface preparation and protective coating

2.3.3 Requirements Associated to Fish Welfare

Policy makers and consumers are increasingly engaged in the husbandry practice and the related fish welfare issues as the aquaculture industry rapidly expands [13]. With this, a long list of laws, regulations and guidelines followed to protect and ensure fish welfare in all life stages, e.g. /001/, /002a+b/ and /003/. Requirements associated with fish welfare affecting this project is recapitulated in Appendix B.1.

Water Quality Parameters
The significant water quality parameters to salmon in fish farms are gathered and published by the Norwegian Food Safety Authority (NFSA). The parameters are divided into four levels based on the measured quantity: optimum, acceptable, conditional and unacceptable. The industry should strive to achieve the *optimum* level to provide the best possible aquaculture conditions for their salmon. Following is the second most optimal quality level: *acceptable*. According to the NFSA, this level is usually achieved by the breeders. If the fish is exposed to one parameter from the *conditional* level, all the other parameters must be favorable for the fish to live over time. Finally, the *unacceptable* quality level results in increased mortality for the fish stock independent of other favourable conditions present. The Norwegian Food Safety Authority findings are summarized in Table 2.2. [46]

Table 2.2: Water quality levels for salmon.

	Unit	Optimum	Acceptable	Conditional	Unacceptable
Oxygen saturation	%	100	60	50	$\leq$40
pH		6.5-6.7	5.7-6.5	5.0	<5.0
aluminium	μg/l	0	15-20	-	-
Iron	μg/l	-	-	300-500	>1000
CO_2	mg/l	1-10	10-40	60	100
Ammonia	μg/l	<2	2-25	25-70	70

2.3.4 Design Requirements

Standard no. /004/ comprises the directions associated with the engineering of buildings and structural work in aluminium in addition to contain the requirements for the serviceability and safety of the structures. The document further contributes to material properties, guidelines for structural analysis, design recommendations, joining methods and other general rules for aluminium construction, which are all relevant to this project. [12]

Table 2.3 presents the outlined material constants specified by the standard.

Table 2.3: Material constants for aluminium.

Property	**Symbol**	**Value**	**Unit**
Modulus of elasticity	E	70 000	N/mm^2
Shear modulus	G	27 000	N/mm^2
Poisson's ratio	ν	0.3	
Coefficient of linear thermal expansion	a	23×10^{-6}	per °C
Unit mass	ρ	2 700	kg/m^3

2.3.5 Environmental Requirements

Regulation no. /002a/ and /003/ refer to NS 9410 or another equivalent international standard where the topic is requirements related to environmental monitoring of the aquaculture site [17][19]. To assure sustainable and legal operations, the fish farm must comply with the statutory rules.

When applying for a fish farming licence from the Norwegian Directorate of Fisheries, the directorate demands specific documentation from the breeder and development company. The documentation required is listed in NS 9410, standard no. /005/ in the previously presented table. Included in the standard is for example how to cover necessary map information and results from trend analysis of the benthic impact. Another equivalent international standard can also be implemented to find the required information. [41]

2.3.6 Site Survey

In NS 9415, the sites for marine fish farms are classified based on significant wave height, H_s and midcurrent, v_c. According to Fredheim & Langan, the authors of "Advances in technology for off-shore and open ocean finfish aquacultur" [21], the commercially available net-pen cages are certified for sites with significant wave heights up to 3m and and current strengths of 1.5m/s. This corresponds to *High exposure* designation within both the wave height and current exposure classification given in NS 9415. The Norwegian Standard classification is presented in Table 2.4 and Table 2.5. Inspections and descriptions of the site shall also be according to NS 9415.

Table 2.4: Site exposure designation by wave height.

Wave classes	Significant wave height, H_s [m]	Peak wave period, T_p [s]	Designation
A	0.0 - 0.5	0.0 - 2.0	Little exposure
B	0.5 - 1.0	1.6 - 3.2	Substantial exposure
C	1.0 -2.0	2.5 - 5.1	Substantial exposure
D	2.0 - 3.0	4.0 - 6.7	High exposure
E	>3.0	5.3 - 18.0	Extreme exposure

Table 2.5: Site exposure designation by midcurrent.

Current classes	Midcurrent, v_c [m/s]	Designation
a	0.0 - 0.3	Little exposure
b	0.3 - 0.5	Moderate exposure
c	0.5 -1.0	Substantial exposure
d	1.0 - 1.5	High exposure
e	>1.5	Extreme exposure

The environmental conditions are highly dependant on where the fish farm is located, e.g. in a sheltered fjord near a coast line or at open ocean waters. Thus, the latter listed current components are expected to be much higher and more critical in the open sea than near the coast line. These environmental variations are the reason why a thorough site survey is required for all future aquaculture locations in Norway.

According to NS 9415, the critical current components to marine fish farms are [42]:

- Tidewater current.
- Wind-induced surface current.
- Outbreak from the coastal current.
- Spring flood because of snow and ice melting.

Location Report Example
A summary of a location report is presented in Table 2.6 to visualize how the location data may occur. The site survey is executed in Storvika, Bodø in accordance with NS 9415 and the measured values are provided by an independent third party. The 10-years wind and 50-years wind for determination of waves is decided in accordance with NS-EN 1991-1-4.

Table 2.6: Summary of location report for TechnipFMC.

[60]

Load Factor			**Return Period**		**Direction**
			10 years	50 years	
Wind wave	Significant wave height / peak wave period	H_s [m] / T_p [s]	1.4 / 4.1	1.5 / 4.3	from 103°
Sea wave			N/A		
Current velocity		v_c [m/s]	0.52	0.58	towards 280°
Wind velocity	Fundamental value	$v_{b,o}$ [m/s]		30	
	Mean wind velocity	v_m [m/s]	27	30	from SE, SW and W
Estimated ice accumulation over three days		[m]	0.44		At low temperatures and strong wind from east
Floating ica			May occure at location		

2.3.7 Load and Load Combinations

To better understand the extensive load scenario associated with closed aquacultures, refer to Appendix B.2 which comprises the outlined load scenarios from standard NS 9415. A thorough analysis of the load effects at the site of interest is crucial to avoid hazardous and wrong use of the fish farm or constructional failure. Load factors for the different load combinations can also be looked up in NS 9415. [42]

Further research on hydrodynamic forces is presented in Section 2.4 to point out the complex load scenario of a floating body with an internal water volume.

2.3.8 Surface Preparation and Coating

The well-known standard NORSOK M-501 from the Norwegian petroleum industry is also suitable for guidance regarding surface preparation and coating in this project. The standard is listed as no. /007/ in the table above and it contains the requirements for surface pre-treatment, selection of coating method and materials, and inspection of coated surfaces [40].

The standard aims to propose guidelines and recommendations to obtain a coating system, which ensures:

- optimal protection of the installation with a minimum need for maintenance,
- that the coating system is maintenance friendly,
- that the coating system is application friendly,
- that, health, safety and environmental impacts are evaluated and documented.

Decisions made concerning surface preparations and coating should be controlled with NORSOK M-501 to ensure a reliable product with a predictable lifetime. On the other hand, the standard does not aim to propose guidelines specific for the aquaculture industry which may affect the feasibility of the recommendations.

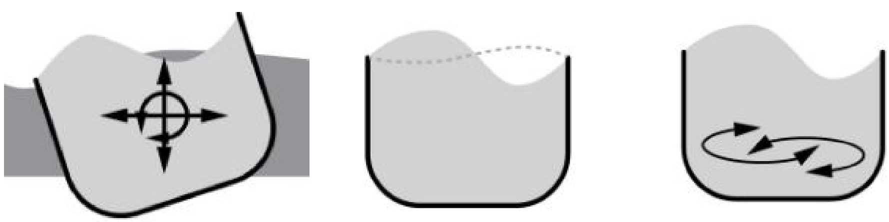
2.4 Hydrodynamic Loads

The identification and calculation of hydrodynamic loads induced on a floating structure with an internal water volume is extremely advanced. It does not, at the time of writing, exist computer models that can predict the movement of the internal water volume and the loads it generates. Leading experts are worried that movement of the internal water volume in closed aquaculture systems can create large forces and be a critical factor for failure. SINTEF is at the time of writing working on identifying and mapping the forces on floating, closed aquaculture systems. [52]

This thesis will not go in depth of hydrodynamic theory or calculations, but will present some of SINTEF's research on the behaviour of closed aquaculture systems in waves, as presented in the pre-study [28]. This will serve to highlight the challenges of developing such structures and the need for further research. This is by no means a complete summary of the hydrodynamic loads, and a more thorough research is crucial for further development. A substantial resource for hydrodynamic loads on offshore structures is the "DNV Recommended Practice DNV-RP-C205 on Environmental Conditions and Environmental Loads" from DNV-GL [11].

2.4.1 Wave Response

Fish farming in closed cages is associated with a complex wave response. In addition to the structural response, is the internal wave response (sloshing) and the applied internal flow of the water volume, as seen in Figure 2.1. To develop a safe and feasible fish farm, it is essential to understand and control the structural responses. As of today there is no known numerical model for simulating the behaviour of closed aquaculture cages, thus developing a numerical code to predict the behavior is highly relevant for future work in TechnipFMC. [47]



(a) Structural response. **(b)** Sloshing. **(c)** Internal flow.

[47]

Figure 2.1: Wave responses and applied internal flow.

Structural response is the global movement of the fish farm. This is the response generated by environmental loads such as wind, waves, current and ice [42]. The behaviour is highly different from what a net based cage experiences, where the water can move nearly without restriction in and out of the enclosed volume [47]. Furthermore, sloshing is induced by displacement of the fish pen because of the external forces. The phenomena is recognized by large movements of the internal water volume, comparable to when a person carries a full cup of coffee. On top of these responses is the applied internal flow which is induced to give optimal and stable conditions for the fish. By controlling the internal flow and minimize sloshing, the fish experiences less stress and better growth, according to Johansen at TechnipFMC.

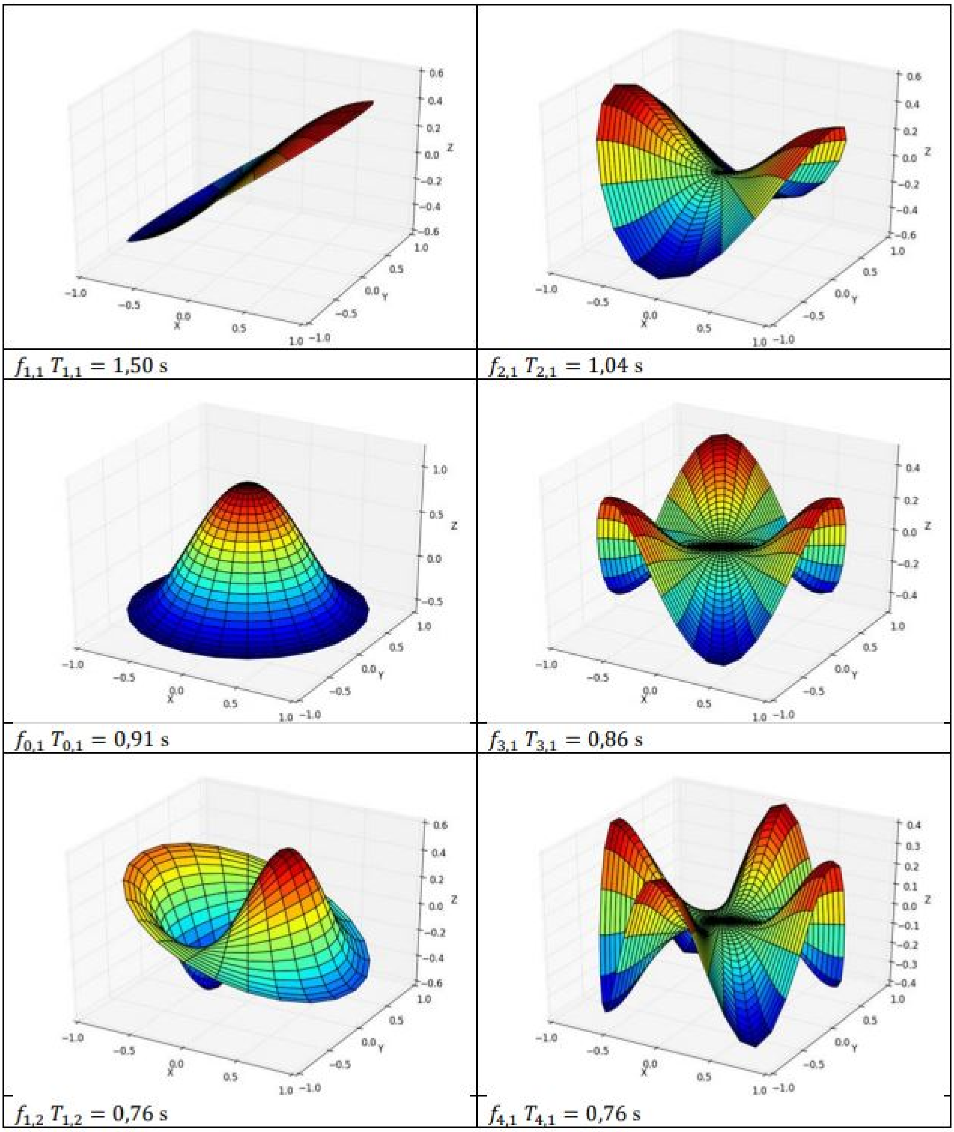
2.4.2 Sloshing

Sloshing depends on water volume, the geometry of the constructions and the responses to the applied external forces [32]. Internal wave response is the outcome of continuous periodic motions of the closed fish farm. The degree of sloshing depends on the period length, T, measured in seconds. Wave responses, or eigenmodes, for sloshing in a horizontal circular cylindrical container is given by Faltinsen & Timokha [14]:

$$f_{m,n}(r,\theta) = J_m(l_{m,n}\frac{r}{R})\left\{ \begin{array}{l} cos(m\theta) \\ sin(m\theta) \end{array} \right.$$

where $m = 0, 1, 2, \ldots$ and $n = 1, 2, 3, \ldots$ and $l_{m,n}$ denotes the roots of the equation $J\,'(l_{m,n}) = 0$. Eigenmodes for the six highest natural periods for sloshing in a circular cylindrical container is illustrated by SINTEF in Figure 2.2 [32].

To avoid structural movements near the sloshing resonance, the structure must be designed to local conditions. This points out the importance of a comprehensive site survey during the development phase of the fish farm which is a requirement from the standard NS 9415 [42]. The local conditions will affect the possibilities of feasible concepts.



[32]

Figure 2.2: Eigenmodes for the six highest natural periods for sloshing in a circular cylindrical container.

2.4.3 Stability

Initial static stability of a closed fish farm is calculated with the same metacentric height (GM) equation as ships and other floating bodies. The following floating stability theory is based on the book "Havromsteknologier" written by H. Holm for the Department of Marine Technology at NTNU [22]. It is calculated as the distance between the centre of gravity (G) and the metacentre (M):

$$GM = KB + BM - KG$$

Line of keel (K) is chosen as reference for the centres. KB is the distance to the centre of buoyancy, BM is the distance from the centre of buoyancy to the metacentre and KG is the distance from the keel to the centre of gravity. Figure 2.3 illustrates the conditions of a floating body. The vertical distance between the centre of buoyancy to the centre of gravity is found by:

$$BM = \frac{I}{\nabla}$$

where I is the 2nd area of moment and ∇ is the volume of displacement. The criteria for static stability is given by $GM > 0$. [22]

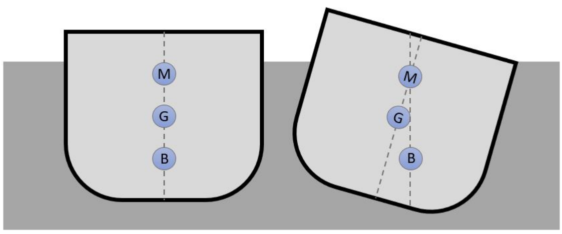
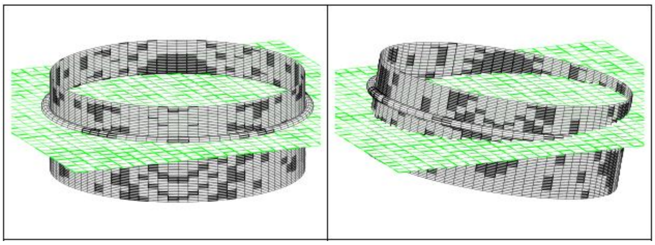


Figure 2.3: Stability diagram of floating body.

Free water surface in a closed fish farm affects wave induced motion and reduces stability when heeling. When the cage heels, the centre of gravity moves vertically and the righting moment decreases. Also, additional floating equipment, e.g. a collar, will negatively effect the righting moment according to SINTEF as the righting moment depends on the waterline area; a decreasing area, decreases the righting moment. The phenomenon is illustrated in Figure 2.4. These effects should be accounted for when predicting stability. [32]



[32]

Figure 2.4: Reduction of righting moment due to submerged collar.

2.5 Aluminium in Marine Applications

This section will introduce the most common aluminium alloys utilized in marine applications, how they behave in a corrosive marine environment and the most common production methods. The main goal of this section is to create an overview of the possibilities and limitations aluminium offers, an overview of the common corrosion mechanisms on aluminium in seawater, and how these factors affect the design. A material analysis study of a floating, uncoated aluminium structure which was stationed in the North Sea for over 30 years, the North Sea Buoy II, will be presented as an example. This section is based on research done in the pre-study, and will not go as detailed into the different aspects of aluminium [28].

2.5.1 Marine Aluminium Alloys

Aluminium is widely used in marine applications because of its high strength to weight ratio and good corrosion resistance. At one third the weight of steel, utilizing aluminium can result in considerable cost savings in transportation and assembly. Unlike other common structural metals, aluminium is the easiest of structural metals to recycle. It can be recycled directly back into high-quality products, creating an economical and environmental advantage. The high formability of aluminium gives the opportunity to produce profiles with complex geometries, specialized for its use. Pure aluminium however has very low strength and is very ductile. The strength necessary for structural utilization is achieved by addition of alloying elements, and plastic or thermal processing. Introducing alloying elements affects strength, hardness, corrosion, weldability, ductility and workability. [29]

In marine applications the most common alloying elements are magnesium and silicon. Magnesium improves the metals strain-hardening properties and its corrosion resistance. Silicon improves strength, and allows precipitation hardening when combined with magnesium as an alloying element. These alloys can achieve a specific strength-to-weight ratio three times higher than steel. Other alloying elements exists, but are not commonly utilized in marine environments. Alloys with more noble allying elements, such as copper, must be avoided in marine environments as they greatly reduce corrosion resistance. [9]

The European Standard for aluminium alloy designation divides the alloys into different series based on the alloying elements, and also differentiates between wrought and cast aluminium [43]. Wrought aluminium for forming is designated with AW for Aluminium Wrought. Cast aluminium will not be mentioned in this paper as they are not commonly used for structural components. Aluminium alloyed with magnesium are designated to the 5000-series, and aluminium alloyed with both magnesium and silicon to the 6000-series. A more thorough explanation of the alloy designation system is presented in the pre-study [28].

To further enhance the properties of the metal, the different aluminium alloy can be strain hardened or thermally treated. Strain hardening, often referred to as work hardening, increases the hardness and tensile strength of the alloy, but reduces its ductility. Higher amounts of magnesium also decreases the ductility, making it possible for manufacturers to tailor magnesium alloys to the strength and ductility needed. Thermal treating, or heat-treating, can increase the strength of alloys by solution heat treatment and ageing. A more detailed explanation of strain hardening and thermal treating is found in the pre-study [28], and the notations are presented in Table C.1 in Appendix C.1. [29]

The 5000 and 6000 series are commonly used in the marine environment because of their good corrosion resistance, great weldability and relatively high strength. The corrosion resistance of the alloys are so significant that they can even be used without protection in marine environments [66]. Unlike steel which becomes more brittle in low temperatures, the 5000 and 6000 alloys becomes stronger and remains ductile at lower temperatures, making it applicable even in arctic climates. The 5000 series is strain-hardenable and is often used in plates, but can also be extruded. The 6000 series which contains magnesium and silicon has a greater extrudability than the 5000 series, making it more suitable for complex profiles. The 6000 alloys are heat treatable and can be solution heat treated directly from extrusion temperature. Some of the 6000 alloys also contains copper, making them unsuitable for marine applications. The most common of the 5000 and 6000 series alloys utilized in marine environment are the 5083 and 6082 alloys. [29]

The manufacturing methods available, and the alloys availability in the market are important when choosing an alloy. The 5000 and 6000 series alloys are widely used in both ship building, offshore structures, and subsea installations in Norway. Several Norwegian companies have wide experience in production and construction of aluminium structures for marine environment. This expertise is extremely valuable when designing structures for a corrosive environment and large external forces. The next sections will introduce the challenges of corrosion and fouling in seawater and how to best protect an aluminium structure in this environment. The possibilities and limitations of the manufacturing methods will then be discussed, and how the product design can facilitate cost savings.

2.5.2 Corrosion in Seawater

Metallic aluminium is highly reactive with atmospheric oxygen. Any exposed surface will almost instantaneously react and create a thin, passive layer of aluminium oxide, prohibiting further oxidation of the metal. Whenever the surface of aluminium is scratched or otherwise damaged, a new oxide layer will form quickly, making it self repairing. The oxide layer has a lower density than the aluminium, and because of this, the oxide layer can also withstand more deformation without breaking [48]. This self repairing natural oxide layer which prevents further oxidation is what gives aluminium its good corrosion resistance. Together with its natural oxide layer and a suitable design, aluminium has a great potential to withstand the corrosive marine environment. [66]

Seawater is a highly corrosive environment, according to the the NS-EN ISO 9223 standard, coastal and offshore environments are in the very high and extreme corrosivity category [2]. The dissolution rate of aluminium oxide depends on the pH values of its environment, and in an aquatic environment it will also depend on the quantity of anions such as chloride. One of the main factors for seawater's corrosive properties is the abundance of chlorides, both from potassium chloride (NaCl) and magnesium chloride ($MgCl_2$). The North Sea contains around 16-17g/l chlorides [31]. Even though the pH value of seawater, at approximately 8-8.5 near the surface, is within the domain of stability of the natural oxide layer, the aluminium can still be prone to pitting corrosion. Seawater also contains 6-8mg/l dissolved oxygen. Oxygen accelerates corrosion by depolarizing the cathodes, but it also repairs the natural oxide layer. The concentration of oxygen in seawater decreases with increasing depth because of the increased amount of biological activity using oxygen for decomposition. The other factors making seawater an aggressively corrosive environment is its low resistivity of only 10Ω which facilitates ionic conductivity and makes galvanic coupling possible. [66][2]

Pitting and Galvanic Corrosion

For the aluminium alloys commercially used in marine industry, pitting corrosion and galvanic corrosion are the most commonly observed types of corrosion. While galvanic corrosion depends on the materials in contact with the aluminium and can be avoided by removing or minimizing galvanic coupling, all aluminium alloys are prone to pitting corrosion in natural environments. [66]

Pitting corrosion is localized corrosion caused by a local rupture of the passive film. These points of attack are most often deactivated by repassivation, by new formation of the oxide layer. In the presence of chloride however, a corrosion pit can propagate. In most cases however, the rate of pitting corrosion in natural environments, such as seawater, decreases over time [66]. The maximum pitting depth rarely exceeds 0.2-1mm after 10 years of immersion in seawater [31]. The decreasing rate of pitting corrosion explains the very long lifetime of aluminium used in marine constructions. It is important to remember that pitting corrosion does not affect the solidity of the aluminium component. [66]

Because of aluminum's relatively high electronegativity compared to other metals, and the low resistivity of seawater, galvanic coupling between aluminium and other metals must be avoided. For example if aluminium is submerged in seawater and in contact with steel, the aluminium will become the anode and steel the cathode, creating an electrochemical reaction between the two metals. The repassivation of the oxide layer will be suppressed, and the aluminium will oxidize critically. By insulating the contact between aluminium and other metals, this electrochemical reaction can be avoided. Tests done in the North Sea on aluminium sheets of the alloy 5083 show that contact with stainless steel is less critical than with unalloyed carbon steel. Even tough aluminium and stainless steel have higher difference in electrochemical potential than aluminium and carbon steel, the passive oxide layers of both metals prohibits galvanic corrosion. [66][9]

Uniform Dissolution

In a marine environment, uniform dissolution of aluminium can occur. The dissolution depends on the water flow speed. At high flow speeds the oxide layer becomes unstable and an uniform dissolution of the oxide layer can occur. The high flow speed is then able to mechanically erode the oxide layer. Measurements carried out in the Trondheim Fjord by SINTEF, with a water temperature of 9°C showed that the uniform metal dissolution rate increased from 0.01mm/year to 0.06mm/year when increasing the flow rate from 0.08m/s to 1m/s, independent of the alloy composition [31]. If the water flow speeds are significantly high, this needs to be taken into account in the design.

Crevice Corrosion

In a corrosive environment crevice corrosion can occur in narrow spaces with little change of water. The oxygen is consumed in the bottom of the crevice, creating an anodic area. In a submerged environment the anodic reaction will occur in the crevice, while the cathode rection occurs on the outside. This reaction results in the pH falling in the crevice, creating an aggressive corrosive environment. [9]

The principal of crevice corrosion is illustrated in Figure 2.5. Crevice corrosion can be avoided by designing to avoid crevices all together, or filling possible crevices with a sealing compound. Crevices cannot always be avoided, but by

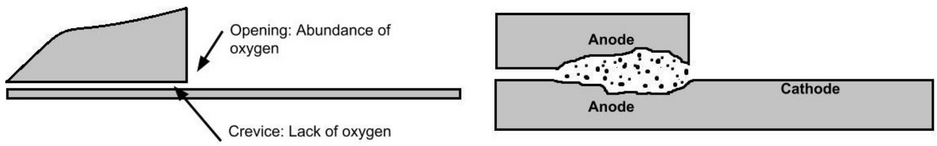


Figure 2.5: The principle of crevice corrosion illustrated.

focusing on the methods and placement of connections, the amount of crevices can be reduced. Some design practices to avoid trapped moisture and crevice corrosion are shown in Appendix D.1.

Intergranular Corrosion

Intergranular corrosion can cause deep, critical corrosion without showing on the aluminium surface. The corrosion develops along the grain boundaries and is difficult to discover. Sensitivity to integranular corrosion is dependent on the alloy composition and heat treatment. The 6000 series are normally resistant to intergranular corrosion, but the 5000 series are at risk if the Mg content is more than 3.5% in temperatures over 60°C. In some alloys the welding can create zones exposed to integranular corrosion, but this is not a problem in the 5000 and 6000 series. [9]

Fouling

Fouling is the forming of biological matter on a surface. When a piece of metal is immersed in seawater, it will quickly become covered by a biological humour on which marine matter such as barnacles, corals, algae, sponges, etc., will develop. Certain metals are unaffected by fouling because its salts are toxic for marine organisms. Copper, mercury and tin are such metals. Aluminium however has no anti-fouling effect, because its salts are non-toxic for marine organisms. Because of this, aluminium immersed in seawater will become covered in marine biological matter. It is however important to notice that the fixation of marine organisms has no critical effect on the corrosion resistance of aluminium [20]. Fouling build-up over time on metals when left unchecked can be immense, adding weight and leaving a very rough surface [57].

In marine industries, an antifouling coating is commonly used to reduce fouling. The fish farming industry commonly uses products containing copper. This will however lead to corrosion due to galvanic connections on aluminium. Because of this the aluminium needs to insulated from the antifouling coating with another coating. As closed fish farming systems have requirements for cleaning on the inside, fouling must be prevented or removed during the cleaning process. Fouling on the outside of an aluminium fish farm structure needs to be further researched to investigate how it will affect the structure. Surface treatment can however help prohibit fouling by making the surface easier to maintain. Information on surface treatment of aluminium can be found in the pre-study, or other resources as the SAPA construction handbook. [28][48]

Corrosion Zones

A floating offshore structure is exposed to different zones with different corrosion behaviour. The aluminium can be immersed, located in the splash zone, or be in a marine atmosphere, as seen in Figure 2.6. As the structure is floating and moves with the tide, there is no tidal zone. In the marine atmospheric zone, corrosion of aluminium is mainly aesthetic. When totally submerged, the aluminium can be protected by cathodic protection. In the splash zone, at the waterline where the environment changes from wet to dry frequently, corrosion is more critical. Because of the different access to oxygen, anodic and cathodic areas can develop and lead to corrosion. Unlike the submerged zone, the splash zone cannot be protected by cathodic protection, and surface treatment is often necessary.

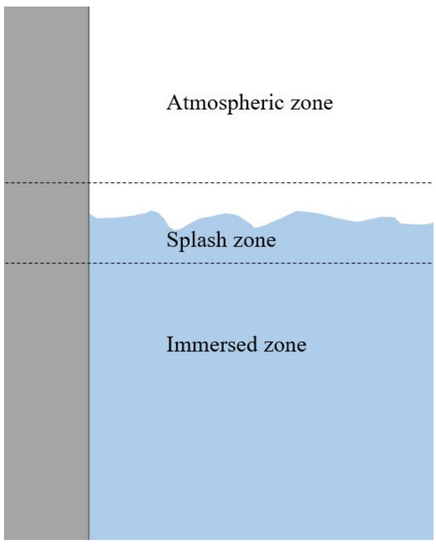


Figure 2.6: Corrosion zones in water.

North Sea Buoy II Example
Figure 2.7 shows the North Sea Buoy II which was examined after 32 years in the North Sea. The buoy was constructed from uncoated aluminium sheets of aluminium alloy 5083 and uncoated profiles of aluminium alloy 6082. The 15m high structure was mostly submerged, and the submerged zone was protected by sacrificial anodes made of zinc, while the zone above water was not protected at all. The buoy was regularly brought to shore and cleaned with high pressure water jets to remove fouling. After 32 years the bouy showed no appreciable loss in wall thickness, nor cracks in the base material or weld seams. The weldability was equal to new material and all stainless steel screws were without defects. [2]

Figure 2.7 also shows how the different zones affect pitting corrosion. On North Sea Buoy II the splash zone experienced 300-500μm pitting depth after 32 years, while the submerged zone only experienced around 100μm pitting depth [58]. This shows how effective the use of sacrificial anodes are for submerged structures. The splash zone generally requires more corrosion protection in marine structures, but as seen from the North Sea Bouy II, aluminium does not corrode critically even after 32 years of service. Aluminium's high corrosion resistance in the splash zone was also further confirmed by tests done on aluminium sheets placed in the splash zone on another test station in the North Sea. The aluminium sheets confirmed that the maximum corrosion depth is reached after a few years, and progresses very slowly after that. [2]

[2]

Figure 2.7: North Sea Buoy II after 32 years in seawater.

Aluminium in Combination with Concrete
An alternative of combining concrete and aluminium structures in the fish farm concept raised a question regarding the benefits and disadvantages of combining the materials. The following section briefly describes the findings from the research.

A research study performed by SINTEF in 1999 revealed a negative effect of aluminium in contact with concrete in moist environments [15]. Aluminium reacts with the alkalies (OH^-) in concrete and produces hydrogen gas and aluminium hydroxide according to the chemical reaction:

$$2Al + 2OH^- + 6H_2O = 2Al(OH)_3 + 3H_2 \tag{2.1}$$

In situations of long-term contact, significant corrosion of aluminium embedded in concrete can occur. The reaction cause expansion of the concrete which may result in destructive cracking of the concrete structure. If the aluminium is in galvanic contact with any ferrous metal, corrosion will also occur. Sacrificial anodes or isolation between the concrete and aluminium will prevent corrosion if combining the two materials can not be avoided.

2.6 Aluminium Manufacturing

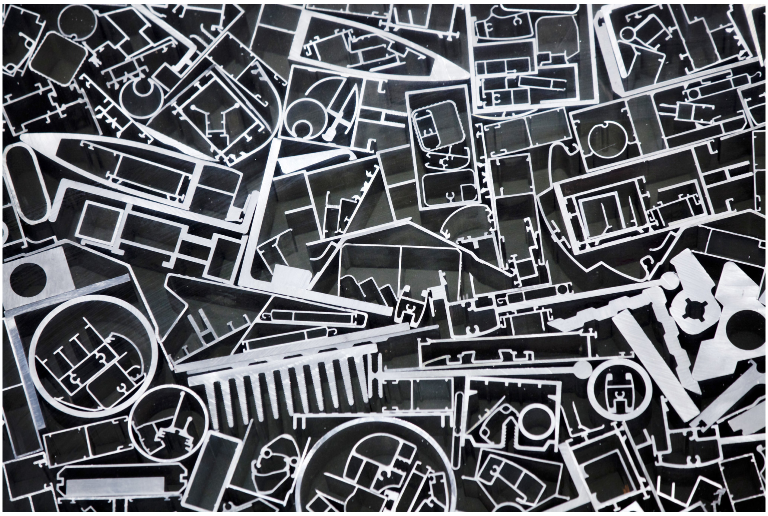
This section will introduce some of the most important manufacturing and joining methods for this project and discuss why knowledge of manufacturing methods is crucial when developing an aluminium structure. It serves as a recapitulation of the research done in the pre-study [28], and for a more thorough overview of different manufacturing methods, the pre-study and the SAPA construction handbook [48] are possible resources.

The design should accommodate modular production and repeatable assembly, and avoid unnecessary manufacturing steps. Knowledge of the common manufacturing methods and joining techniques are essential when developing a cost effective design. Out contacts at Hydro were a great resource for knowledge, and continuous communication should be prioritized to select the best possible alloy and production method. Other experienced constructors were also contacted to validate the feasibility of the concepts and the assembly methods. There is a significant use of aluminium in Norwegian offshore industry, and this experience should be utilized.

2.6.1 Aluminium Extrusion

One of the main advantages of aluminium component production is the extrudability. By heating an aluminium billet up to 450-500°C it is possible to extrude the material through a shaping tool, obtaining precise and advanced profiles. Profiles can be extruded at a speed of 5-50m/min depending on alloy, size and complexity. The profiles are extruded at lengths usually between 25 and 45 meters. The profiles are air or water cooled as they leave the shaping tool, and are stretched to release tension and assure straightness [48].

Design Prerequisites
The complexity of the profile shape will determine the speed of extrusion and the cost of the shaping tool. The profiles are divided into two categories: open profiles and hollow profiles. Open profiles are the easiest and cheapest to produce since they only require one shaping tool. Hollow profiles are more complex and requires several shaping tools to create the closed sections, this increases costs. Figure 2.8 illustrates the wide variety of possible extruded profiles available at Hydro. As seen in Figure 2.9a, some complexity can be avoided by good profile design.



[27]

Figure 2.8: Different extruded aluminium shapes by Hydro.

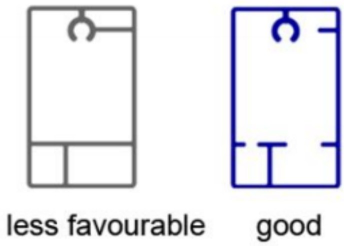
The shaping tools used in extrusion do not represent a large investment, but the complexity of the profile will dictate the lifetime of a tool, and at which rate it can be extruded, making it more expensive [48]. To keep the cost down, profiles should be designed for the easiest production possible while still keeping the desired structural requirements. Extrusion is limited with the width and height of the profile tools. The dimensions available from Hydro are shown in Figure 2.9b.

Factors that simplify extrusion:

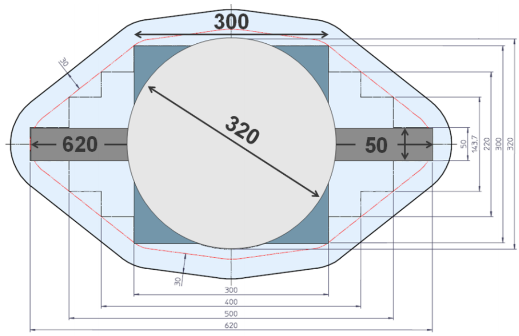
- Simple shapes with rounded corners.
- Even wall thickness.
- Using symmetry.

Factors that complicates extrusion:

- Deep, tight grooves.
- Several hollow sections.



(a) Cost efficient profile design. [9]



(b) Hydro profile extrusion size limitations. [58]

Figure 2.9: Improved profile design and dimension limitations of extrusion tools.

2.6.2 Joining Techniques

There exists a wide variety of joining techniques for aluminium components. Several mechanical joining methods such as screw connections and snap connections can be integrated directly into the design, while others require additional processing. In addition, most aluminium alloys are highly weldable [48]. The most common joining techniques used in aluminium assemblies are:

- Screw and bolt connection
- Snap-on connection
- Gluing and taping
- Integrated hinges
- Fusion welding
- Friction stir welding

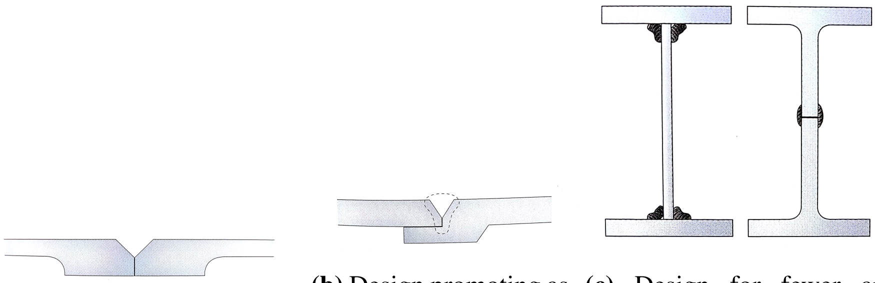
This section will focus on screw and bolt connections, fusion welding, and friction stir welding as they are the most commonly used methods in structures and have the highest mechanical properties. Since our structure is to be submerged in seawater and needs to be water proof, the joining technique must be compatible with water proofing gaskets, or be water proof on its own. Design considerations regarding joining to prohibit corrosion in structures are shown in Appendix D.1.

Screw and Bolt Connections
Screw and bolt connections are very commonly used to join structural components. They have high mechanical properties, are easy to implement and they are cheap. There exists standards for sizes and guidelines for different load cases and implementations. Depending on the forces, the bolts and screws come in both aluminium and in stronger steel. As mentioned in Section 2.5.2, connecting steel bolts directly to aluminium will lead to galvanic corrosion. In any case where there must be a combination of steel and aluminium, the connection must be insulated. Aluminium profiles can be designed to facilitate bolt connections [48]. Utilizing screws and bolts requires good access during assembly, and because of the large amount of screws and bolts required, it can also increase the assembly time.

Fusion Welding
In fusion welding of aluminium the two main methods are Metal Inert Gas (MIG) welding and Tungsten Inert Gas (TIG) welding. Both methods use an electric arc to melt the metal, an inert shielding gas to prohibit oxidation, and a filler metal. MIG and TIG welding can be performed in any position by trained personnel, in addition, MIG welding can be performed by robots. Repairs with fusion welding can also be performed on site. [48]

When fusion welding aluminium, the oxide layer must be taken into account. The oxide layer is strong and have a melting point at around 2050°C and can lead to welding defects. Because of this, the oxide layer must be removed before welding. In normal atmosphere the air usually contains moisture, and the hydrogen in the moisture is very soluble in melted aluminium. When a weld solidifies, trapped hydrogen will create pores in the weld, reducing the density and the mechanical properties of the weld. In any fusion welding operation the surface must also be cleaned to avoid trapping contamination in the weld. [48]

The temperatures which the aluminium is exposed to during fusion welding will locally change the structure of the metal by increasing the grain size. Increased grain size reduces the materials mechanical properties, making the heat-affected zone (HAZ) more exposed to fracture. Different aluminium alloys are used as filler metals depending on the application, possibly creating welds with different chemical composition than the component. Profiles used in welding are often designed with increased wall thickness near the HAZ to counteract the reduction in strength, see Figure 2.10a. The increased temperature can also induce stresses in the material and distort the component. [48]



(a) Increased wall thickness. (b) Design promoting assembly. (c) Design for fewer and stronger welds.

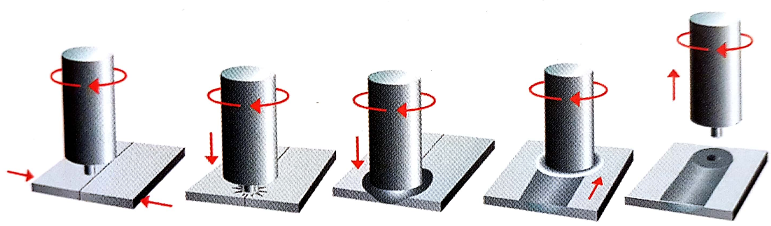
[48]

Figure 2.10: Improved design for stronger, more precise and optimal welds.

When a structure is to be joined with fusion welding the aluminium profiles can be designed to facilitate welding. Smart profile design will reduce the amount of welds and make welding easier where it is necessary. It is important to avoid welding in high stress zones whenever possible. Figure 2.10b shows a design where one component supports the other during welding, making preparation for welding easier and faster. Figure 2.10c shows how design and planning will reduce the amounts of welds and places the weld in a less stress intensive zone. It is important to remember that gaps that are not welded must be sealed to avoid crevice corrosion. [48]

Friction Stir Welding

Friction Stir Welding (FSW) utilizes aluminium's ability to resist extreme plastic deformation at high temperatures (under the melting point). The method uses friction from a rotating, stirring, tool and pressure to create a homogeneous weld between two components, as seen in Figure 2.11.

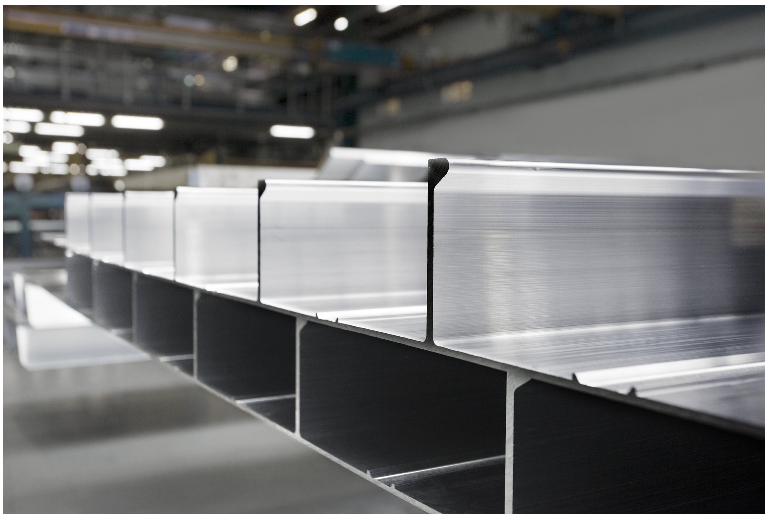


[48]

Figure 2.11: Principal of friction stir welding.

FSW gives a weld with higher strength and higher density than fusion welding. The method creates a weld without pores or inclusions. The operation does not generate the high temperatures as in fusion welding, minimizing thermal stress in the welded component. Unlike fusion welding which creates a weld ridge that must be removed to get a plane surface, FSW creates a weld that is almost flush with the surface [48]. No shielding gasses or filler metal are required, making the weld identical to the component in chemical composition. FSW must be done by machines and requires a rigid rig setup and a flat welding surface. Once the rig is set up for production, the operation is highly repeatable, but it limits FSW to be done in the production facilities, making repairs with FSW on site impossible. [48]

Hydro is able to create up to 3m wide and 16m long panels by friction stir welding extruded profiles together. Compared to rolling which can implement some corrugation to panels, FSW makes it possible to create complex panels with all the advantages of extrusion structure design. FSW panels are widely used in shipbuilding because of the combination of large panels with high strength and added stiffening structure. A resulting friction weld on a hollow profile is illustrated in Figure 2.12.



[27]

Figure 2.12: Hollow aluminium profiles welded with FSW.

2.7 Scaling Theory

In the research phase, it was concluded that model scale testing should be considered for further, essential educational outcome. Lader at the Department of Marine Technology, NTNU advised against the execution of technical validated tests in mid-March 2019 due to its comprehensive extent and the limited time frame remaining of the project. For later model tests, the pool site at NTNU is available for rental when TechnipFMC concludes that testing is appropriate. Also according to DNV-GL's recommended practise, item 7.3.10.3, performing tests will at one point be highly necessary to understand the behaviour of the fish farm: "*Numerical predictions of loads due to sloshing in internal tanks should be combined with model test. Computer programs (CFD) are still not able to predict wave breaking in tanks and resulting local impact loads*" [11].

Because of the importance of model scale testing, the scaling theory is included in this thesis to facilitate further development. This theory is also the foundation of why model scale testing never was performed as part of this master thesis, because of its complexity and the limited resources available. Based on the lecture note "Experimental Methods in Marine Hydrodynamics" [56] by S. Steen, the following sections recapitulate the issues and requirements connected to scaling.

Experiments connected to model testing of ships date back to the 16th century and the initial experimental recommendations about which design for the ship hull results in the higher speed. No scaling laws were available and one had to assume that the best model corresponded to the best full scale concept. With the increasing interest for the method of using model testing for ship design, a method for scaling from model resistance to the actual ship resistance was established during the 19th century by William Froude.

According to S. Steen, the three different aims of hydrodynamic model testing are [56]:

1 To achieve relevant design data to verify performance of actual concepts for ships and other marine structures.

2 Verification and calibration of theoretical methods and numerical codes.

3 To obtain a better understanding of physical problems.

To transfer these three aims to a closed fish farm system:

1 The concept of closed aluminium fish farms is new and there is little available theory about the actual structural behaviour in marine environments.

2 There is no known numerical model, at the time of writing, that comprehends the extent of the natural sea loads, the movement of the internal water volume (sloshing) and the applied internal flow. Model testing is therefore essential to validate later attempts on developing numerical models.

3 Model testing can increase knowledge and understanding of the interaction between sea loads and structural responses.

Further, it is stated in the lecture note that to achieve similarity in forces between the scaled and full scale model there must be a geometrical, kinematic and dynamic similarity.

2.7.1 Geometrical Similarity

Geometrical similarity implies that the model and full scale have the same shape and it exists a constant length scale λ between them [56]:

$$\lambda = \frac{L_F}{L_M} \tag{2.2}$$

where L_M and L_F are the dimensions of the model and full scale structure respectively. An essential part of the geometrical requirement to constant length ratio for all dimensions also applies to the surrounding environment. An example of the presence of physical boundaries is the restricted water volume in a test pool site which never will correspond to the unlimited extent of water in the sea and thereby can influence the test results.

2.7.2 Kinematic Similarity

It is required that the ratios between velocities in model scale must be equal to the corresponding ratios of the full scale model. An example is the ratio between the rotational speed of the propeller and the speed of a ship, which is not of current interest in this project as a marine fish farm is moored.

2.7.3 Dynamic Similarity

To accomplish dynamic similarity, the ratio of the force contributors for the model scale and full scale model must be equal. A floating body with a large volume submerged in water, like the fish farm, is influenced by both surface wave effects and viscous forces, which implies that equality in Froude number and Reynolds number in principle should be achieved. Though, scaling the viscous forces is not possible to achieve according to S. Steen, so the scaling process of the viscous effect must be evaluated carefully before any conclusions are made.

The surface wave formation is governed by gravitational forces. To secure dynamic similarity is the ratio between inertia and gravity forces studied. The inertia force is given by:

$$F_i \propto \rho \frac{dU}{dt} L^3 = \rho \frac{dU}{dx}\frac{dx}{dt} L^3 = \rho U^2 L^2 \tag{2.3}$$

and the gravitational force is given by:

$$F_g \propto \rho g L^3 \tag{2.4}$$

where ρ is fluid density, U is velocity, L is physical length and g is gravitational acceleration [56]. Resulting is the ratio:

$$\frac{F_i}{F_g} \propto \frac{\rho U^2 L^2}{\rho g L^3} = \frac{U^2}{gL} \tag{2.5}$$

When the method for scaling is applied on model and full scale the requirements give

$$\frac{{U_M}^2}{gL_M} = \frac{{U_F}^2}{gL_F} \tag{2.6}$$

$$\frac{U_M}{\sqrt{gL_M}} = \frac{U_F}{\sqrt{gL_F}} = F_N \tag{2.7}$$

where F_N is the Froude number. If geometrical similarity, kinematic similarity and equal Froude number are obtained in both the model and full scale, also the similarity between inertia and gravity forces is achieved [56]. The viscous force is characterized by the equation:

$$F_v \propto \mu \frac{dU}{dx} L^2 = \mu U L \tag{2.8}$$

If the viscous forces are to be correctly scaled, the ratio between inertia and viscous forces will give the Reynolds number, Re:

$$\frac{F_i}{F_v} \propto \frac{\rho U^2 L^2}{\rho U L} = \frac{\rho U L}{\mu} = \frac{UL}{\nu} = Re \tag{2.9}$$

and the kinematic viscosity is expressed by $\nu = \mu/\rho$ [56].

2.7.4 Hydroelasticity

Modelling of elastic properties in hydroelastic problems gives additional challenges compared to the modelling of rigid structures influenced by wave effects. Correctly scaled elastic behaviour is assumed to be essential for the mooring lines and partly or fully flexible fish farms to predict the structural responses.

An elastic model has the following additional requirements, according to S. Steen [56]:

1 Global structural stiffness shall be correctly scaled.

2 Structural damping must be equal for the model scale and full scale.

3 Equal mass distribution in both cases.

Following is the deflection of a cantilever beam considered to illustrate an example. The example is based on the S. Steen's lecture note [56]. To ensure geometric similarity, the deflection δ shall correspond in the model and full scale. The deflection is given by:

$$\delta \propto \frac{FL^3}{EI} \tag{2.10}$$

where F is the hydrodynamic force expressed by

$$F \propto C\rho U^2 L^2 \tag{2.11}$$

and EI is the flexural rigidity. The force coefficient C depends on the Froude number, Reynolds number etc. The deformation requirement applied on model and full scale gives:

$$\frac{\delta_F}{L_F} = \frac{\delta_M}{L_M} \Rightarrow \delta_F = \lambda \delta_M \tag{2.12}$$

Combining the above equations, Equation 2.12 is satisfied if

$$\frac{C\rho U^2 L^4}{EI} \tag{2.13}$$

is the same in both the model scale and full scale. If the force coefficient, C, and density, ρ, are equal is the following requirement to structural rigidity found by:

$$\left(\frac{U^2L^4}{EI}\right)_F = \left(\frac{U^2L^4}{EI}\right)_M \Rightarrow (EI)_F = (EI)_M \lambda^5 \tag{2.14}$$

If the dimensions of the cross-section of the beam are scaled according to the geometrical similarity, the second moment of inertia, I satisfies

$$I_F = I_M \lambda^4 \tag{2.15}$$

From this, the requirement to the Young's modulus, E, is found to be:

$$E_F = E_M \lambda \tag{2.16}$$

which implies that the Young's modulus for the full scale structure is λ times the value of the model scale. Note that in practical model testing the requirement for EI may be manipulated by applying other materials, other wall thickness or shape of cross-section. This is highly relevant information for later decisions affecting the scale model material alternatives and dimensions. For example utilizing other materials than aluminium in the scale model is cost efficient and facilitates rapid prototyping by 3D-printing or other materials and processes.

2.8 Modular Product Development Theory

As the market for closed fish farms is expected to increase over the next decade, the suppliers race to develop the best possible solutions to offer the customers. A global business company like TechnipFMC must also expect a large range of individuality of customer demands tailored to suit their particular needs. The evolving conflict between external variance and internal standardization can be solved by approaches like modular product design [33].

Products with modular architecture are recognized by the elements of its design which are split up and broken down into standardized modules. Later, a selection of the modules are put together to build the demanded product. A modular design will increase the flexibility of the system by enabling an increased number of possible configurations based on the same set of modules available [50].

The purpose of modularity in design is to:

- make the complexity of a system manageable;
- enable parallel work at the set of modules; and
- accommodate future uncertainty. [4]

The benefit of accommodating for future uncertainty is highly relevant in this project since the development of concepts and gathering of knowledge happens in parallel. This means, when the scope of this thesis and all requirements of the modules are established, there are still a lot of details and information that is not determined or yet developed. This calls attention to the fact that the modules must be defined thoroughly to allow for the modules to be changed and further improved in the future. The descriptions of the modules should include interface specifications, how the modules perform their tasks and how the modules interact and depend on the other components. [49]

Implementing the mindset of modular architecture while developing the fish farm concepts helps to organize the system into accessible building blocks. Reduced complexity and reduced component variety in production are expected to lower the rate of production errors and decrease the lead time. Standardization of production tools and assembly equipment is also a major opportunity to cut costs. Further, allowing for interchangeability within the modules will increase the product variety offered on the market, without significant revolutions. [33]

There are also considerable risks connected to modularization, such as high implementation costs and the risk of pursuing a less than maximal degree of modularity. Not all projects, or companies, have the required recourse to implement modularization in their products. As the approach of modular product development mainly is implemented as a design mindset and to inspire our concept development, the risks are less critical to this project. [33]

Chapter 3

Results

The methodologies described in Section 1.4 outlines the theoretical foundation applied to increase the resulting outcome of the development process. According to step 1 of the SBCE methodology, the first project task is to map the design space by investigating the feasible regions, design multiple alternatives, explore trade-offs and communicate sets of possibilities [54]. With the theoretical foundation presented in Chapter 2, a presentation of the multiple generated concepts and investigated sets follows.

The methods implemented in the design phases are further described in this chapter together with a chronological overview of the explored concept sets. When more facts were needed to proceed with the development, either a dialogue with experienced workers or literature studies were performed. Employees at TechnipFMC, Hydro and Marine Aluminium, among others, participated in the evaluation process of the generated concepts to enhance the procedure of eliminating the least feasible ideas and challenge the concepts with critical questioning.

The initial concept development phase presented in Section 3.1 is founded from the results in the pre-study [28] leading to this thesis. The second development phase, presented in Section 3.2, is performed during the spring semester and explores solutions for different subsystems of the structure. Certain details from the concept development are not revealed in this thesis as they are under development from TechnipFMC, and not open to the public.

The generated concepts are discussed and evaluated based on the following factors:

- Modularity
- Scalability
- Simple manufacturing
- Simple joining and assembling
- Land-based transportation

To illustrate the results from the development process and point out the achievements of the second SBCE methodology step, Figure 3.1 presents a map of the extent of the project. Intersections of different sets investigated lead to combining of the ideas and growth of new solution alternatives. The alternative sets are evaluated on a high level, meaning that no detailed design is carried out or final dimension decisions are decided. Before committing to one of the alternatives the concepts are investigated, discussed and evaluated by the students and later by external contacts. This in accordance with step 3 of the SBCE methodology; establish feasibility before commitment [54]. As can be seen from the figure, the later development stayed within the sets once committed to push the work further.

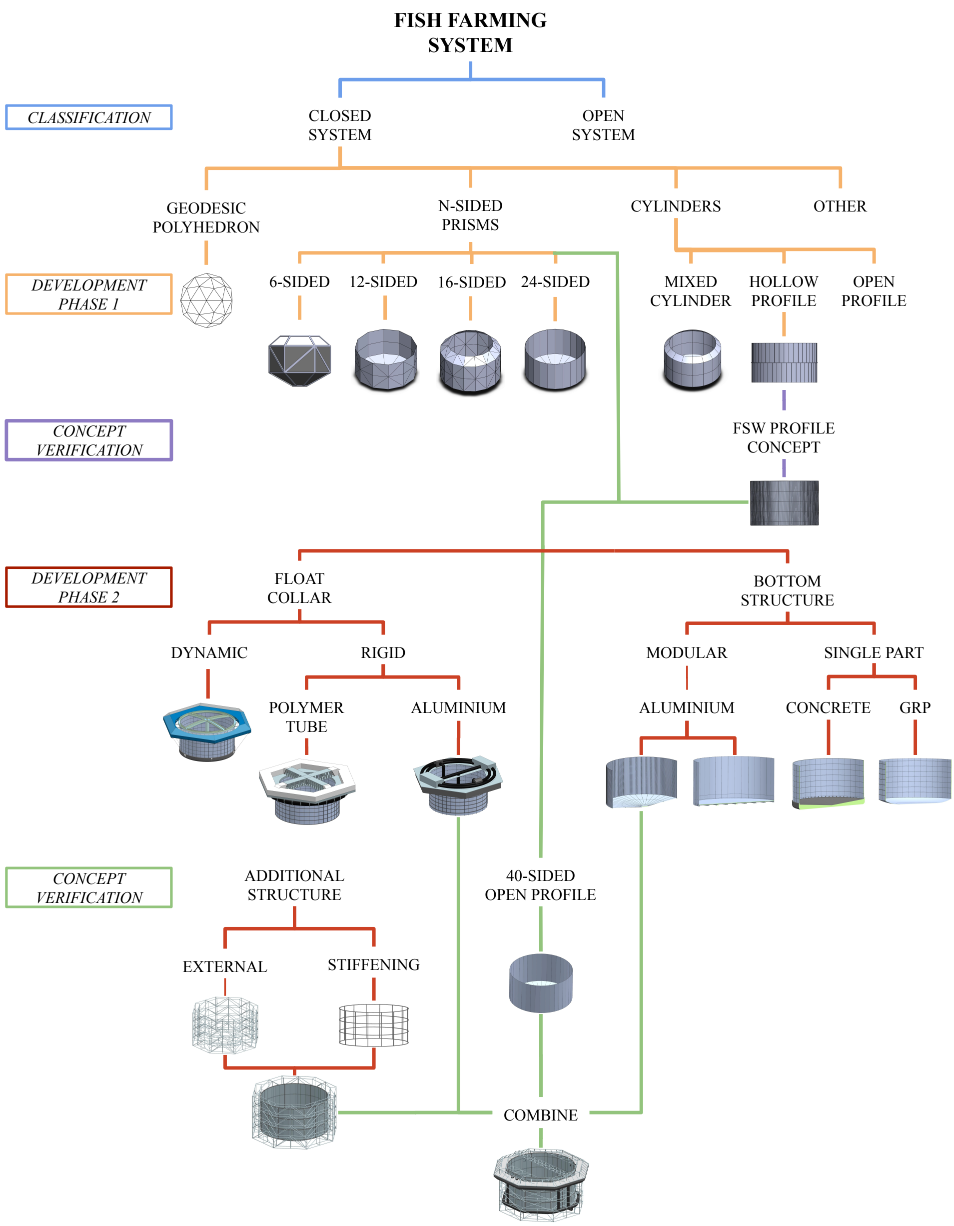


Figure 3.1: Overview of the whole development progress and scope.

3.1 Development Phase 1

A method that was advantageous during the initial development period was the Morphological Chart. The method is described in the thesis "A theoretical approach to mechatronic design" [10], and can be summed up in four steps:

1 Identify main functions of the design.

2 Control that all functions are independent.

3 Attach alternative means for the realization of each function.

4 Generate design concepts by forming possible combinations of means for each function.

The method helps discovering the solution space for fish farm concept solutions by the generation of numerous possible ideas. This corresponds with the first SBCE principle described in Section 1.4.1 where the aim is to map the design space. The combinations of means were visualized and clarified by both rapid sketches and simple 3D-models. The visual communication of concepts is a crucial tool to promote understanding, verification and further ideation. Finally, an evaluation session helped detect and list the advantages and disadvantages of each concept in means of feasibility and quality of the outcome. The outcome of this evaluation session is presented in Section 3.1.7.

Before concept development could commence, the newly explored and broad design space were to be narrowed down by the location in which the aquaculture system would be applied. It is not feasible to develop a system of this size that can be utilized both on land and at sea. The application location was then narrowed down to at sea, sheltered from the worst waves and currents. This location utilizes the geography of Norway with its many fjords. The choice of material was predetermined, as this thesis aims to explore the possibility to introduce aluminium to the industry. However, the development was conducted with the possibility to implement other materials where it would be beneficial. It was important to not be locked to aluminium if another material could serve the purpose better. With focus on aluminium and the production methods available, high level concept development could start. During this high level development period the concepts were divided into 3 sets of interest based on their structural appearance:

- Goedesic polyhedrons
- N-sided prisms
- Cylinders

The remaining structural appearances, as illustrated in the Morphological Chart in Figure 3.2, were early rejected due to improper interface towards the sorting mechanism desired by TechnipFMC. Their fish sorting mechanism is thought to be positioned in and revolve around the centre of the construction. This circular motion in a non-cylindrical shape can enable hiding and escape of the fish from the sorting mechanism, hence the structural appearance is a guiding dimension for further development.

Functions	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Location	Open sea	Fjord	Onshore	Onshore Close to sea	Indoor	
Structural appearance						
Primary module shape						
Joining method	Screw and bolt connection	Snap-on connection	Gluing and taping	Integrated hinges	Fusion welding	Friction stir welding
Material	Aluminium	Steel	GRP	Concrete	Flexible bag	

Figure 3.2: Morphological chart used to ideate new solution alternatives.

Further, to also achieve an even internal flow with minimal disruptions due to sharp edges or corners are the geodesic polyhedrons, N-sided prisms and cylinders advantageous compared to the rejected structural appearances. The three design sets in focus are further investigated in Section 3.1.1-3.1.3 with respect to the main shape and modularity for low production costs. The following concepts were developed and presented to TechnipFMC, before being presented to the external experts and design engineers.

3.1.1 Geodesic Polyhedron

The geodesic polyhedron domes in Figure 3.3 were the first structural set explored. The structure consists of several triangular elements with straight edges and flat faces put together to approximate a dome or a sphere. To obtain high structural rigidity and stress distribution the triangular elements are preferred rather than a square or polygon. Consisting of only three different strut lengths and hubs to connect the ends, the structure is highly modular and repeatable to assemble [1].

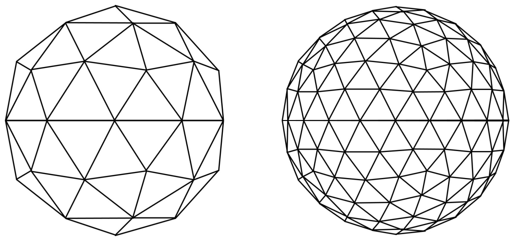


Figure 3.3: Illustration of two types of geodesic polyhedrons.

The geodesic polyhedron sphere was early a preferred structure due to its structural strength and modular composition. On the other hand, the high amount of seams and connection points stood out as a disadvantage in this concept. They form critical areas with regards to leakages, and the interplay with the sorting mechanism can turn out to be challenging. The performance of a sorting mechanism that moves along the structure walls should take into account the existing deviation between the dome structure and a perfect sphere. Finally, when changing the dimensions of the concept, a need for new element sizes appear. Due to this, the process of scaling the concepts in the solution set is complex and requires additional manufacturing and planning.

3.1.2 N-sided Prisms

The second solution set explored was the N-sided prisms, where N is an undetermined number higher than 2. Four prisms were chosen to illustrate this set of structural appearances: 6-sided, 12-sided, 16-sided and 24-sided prisms. The rotating fish sorting mechanism encourages the use of a prism with high N to closely approximate a cylindrical structure; a prism with a high N has a lower deviation from a sphere than a prism with a low N. Also, the concept is modular if the sides are identical and repeated around the whole structure. Triangular elements increase the strength and decrease the element size, which is desirable to improve the structural characteristics.

A 6-sided prism is shown in Figure 3.4 where the triangular elements also represent the opportunities of new material combinations and processing methods. A combination of aluminium profiles and plates of either aluminium or GRP could result in a lighter and more flexible design. However, how the material choice affects the strength and wave response of the system should be examined further together with potential cost increases associated with the production of both plates and profiles. If neither strength or stability is negatively affected or cost is increased, this is an interesting idea to develop further.

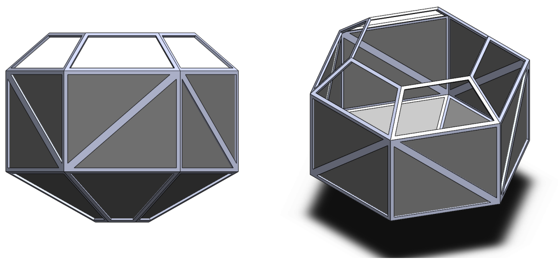
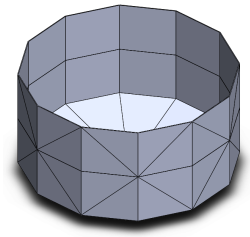


Figure 3.4: 6-sided prism concept with mixed module elements.

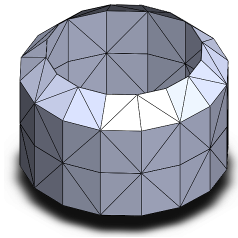
Similar to the joining of the geodesic polyhedron, the N-sided prisms consists of many parts to assemble. Connecting the hubs and joining the seems must be performed precisely to achieve a waterproof and feasible design. Especially for the prisms with a low N, the element dimensions get quite large and may cause comprehensive manufacturing, limited means of transport and handling challenges. To solve this, three other concepts were explored: the 12-sided, 16-sided and 24-sided prisms.

The rewarding effect of a larger N is clearly visible in Figure 3.5 of the 12- and 16-sided prisms when an approximation to a cylinder is the objective. Equal to the earlier described sphere concept, the triangular elements are maintained to substantiate the opportunity of a modular design with high structural strength. The narrowed water line area, as seen in the top of Figure 3.5b, represents the idea of a coherence between area size and sloshing extent generated by external forces. Further investigation of this potential coherence could clarify the uncertainties of this hypothesis and indicate whether a narrow top increases structural stiffness or not.

The last N-sided concept was developed as a solution to minimize the number of manufacturing methods required when combining plates and profiles where wide extruded profiles substitute the combined solution. Figure 3.6 illustrates the con-



(a) 12-sided.



(b) 16-sided.

Figure 3.5: Two N-sided prism concepts with triangular module elements.

cept and the use of a single-part element to build the fish pen walls. The design cuts production costs by the reduced number of manufacturing steps and required element variation. On the other hand, the wide profiles may request for the development of new processing tools which give an initial cost to consider. If redesigning the concept allows for the utilization of standard tools, it will be an improvement. Whether the design requires additional stiffening elements is undetermined at this point but profiles encircling the cage may help increase torsional stiffness if needed.

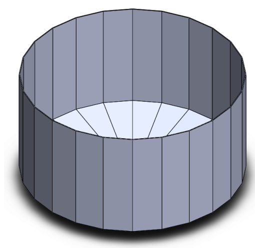


Figure 3.6: 24-sided prism concept with wide profile elements.

3.1.3 Cylindrical

The third and last structural set solutions looked into in this development phase were the cylindrical concepts. Ideation and discussion resulted in two new structures which both take advantage of extrusion as a manufacturing method. The first concept includes bent, hollow profiles as wall elements, as shown in Figure 3.7. These profiles are expected to have better strength properties compared to open profiles. The final decision on profile type is delayed until the strength requirements are available. A disadvantage of the hollow profiles implemented in this design is related to the increased cost and weight; more material results in a higher weight which again increases cost. As described in Section 2.6, hollow profiles are also more complex to manufacture, increasing the cost. It could also be possible that hollow profiles could lead to lower weight in total because of a reduced need for additional stiffening. These trade-offs are discussed further in Section 3.2.4 as a part of development phase 2.

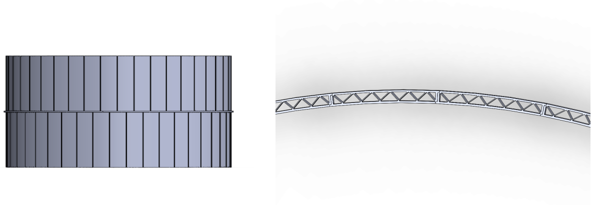


Figure 3.7: Cylindrical concept with hollow profiles.

The second concept developed is seen in Figure 3.8. As the production process with the lowest cost is not initially obvious, the material combination and element type are in this concept undetermined. Still, the structural appearance is evidently modular and the concept is, therefore, put aside for further evaluation and development.

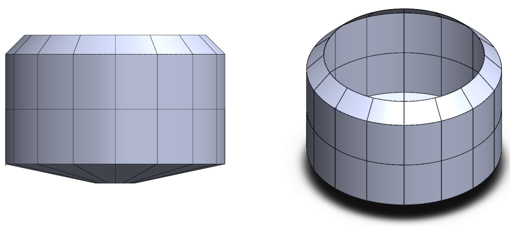


Figure 3.8: Mixed cylinder concept with bent module elements.

3.1.4 Collaboration with TechnipFMC

Weekly Skype meetings were carried out during the fall semester development period to encourage progress and communication with the employees at TechnipFMC. Høgberget, Halvorsen, Høy and supervisor Ringen participated to get an update on the resulting work and contribute with new ideas which grew from the input presented. The meetings were also a platform for us to ask questions about design requests given by the company to ensure a common objective, as misunderstandings can be the reason for wasted time and an undesirable development path. Continuous communication and close follow-up with the collaborators at TechnipFMC is in correlation with the SBCE methodology implemented in the project as described in Section 1.4.1.

One of the frequently discussed topics in the meetings was how to best design for interaction between the main structure and the rotating sorting mechanism TechnipFMC wished to implement. A more detailed description of how the mechanism operates will not be revealed in this thesis as it is under development by TechnipFMC, and not open to the public. The dialogue with TechnipFMC clarified the advantage of the concepts with a smoother surface that can easily interact with a revolving mechanism and also the promotion of concepts with a simple construction that is assumed to be cheaper to produce. An evaluation of the previously presented solution sets with respect to the assumed costs and implementation of a sorting mechanism resulted in the rejection of the geodesic polyhedron solution set.

To discuss the two remaining solution sets further, Halvorsen and Høy travelled to Trondheim for a workshop and an initial meeting with Lader at the Department of Marine Technology. The workshop with the collaborators helped promote a common understanding of the 3D-modelled concepts previously discussed via Skype, and highlighted the need for consultation with experts within aluminium design and manufacturing. Although most communication works well with Skype, face to face collaboration seemed to speed up the progress and simplify the dialogue. The meeting with Lader was to commence further co-operation when in need for test facilities and marine technology expertise.

3.1.5 Concept Verification

To push the development to the next level, the supervisor and employees at TechnipFMC invited a selection of their contacts in Hydro to participate in the weekly Skype-meetings over a months period. The frequent dialogue contributed to the development process with a constant submission of new ideas, feedback and knowledge sharing. As the main goal, the experience-based knowledge of the employees at Hydro was to be implemented as the basis of elimination when evaluating the solution space. In addition, the company is highly relevant for further cooperation and accomplishment of this development project as Hydro is present within all market segments of aluminium [30]. The following sections elaborate on the discussed topics and resulting redesigns developed after this educational period.

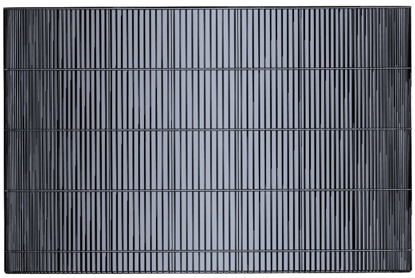
To TechnipFMC, the material and production cost is a decisive factor for whether the project is carried out or not. At the first meeting, the Hydro employees got an introduction to the project and its place in the industry of fish farming. Then the concepts in the solution sets and thoughts about the pros and cons were presented. Svendsen, Olsson and Helander from Hydro supported the decision of rejecting the geodesic polyhedron set as the manufacturing and joining seemed rather complex. They questioned, in general, the benefit of combining plates and profiles rather than only one of them, for example the hollow profile concept in the cylindrical solution set. They pointed out that a simple manufacturing procedure often correlates with a lower cost.

The meetings continued with a focus on the hollow profile concept and how to develop it further and simplify manufacturing. Whether hollow or open profiles are the most suitable for this project remains to be decided. This is often a question of required strength, stiffness and assembly method, and is therefore a decision delayed until the requirements are settled. However, the dialogue encouraged further literature studies on the topic of profile specifications, which was also one of the main topics of the Hydro Profile Academy 2018. As bending could be a part of the intended manufacturing, Hydro pointed out the benefit of open profiles to not negatively influence the strength properties of the elements. Bending a closed profile is often more challenging and may result in unwanted deformation or reduced strength of the profile.

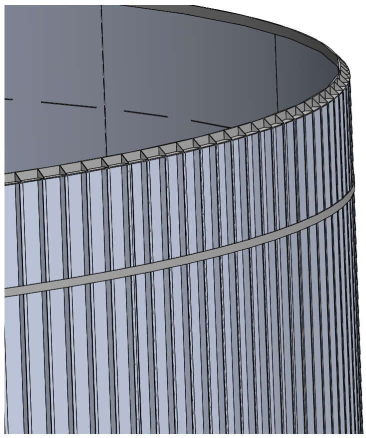
A method to produce aluminium panels with only extruded elements as the main component, is by friction stir welding, see Section 2.6.2. This method is commonly used in aluminium shipbuilding to offer great strength and stiffness, and it allows the implementation of readily available profile designs and manufacturing methods. Hydro offers FSW panels to their customers and advised to use the Hydro Extrusion SeaChange Panel Configurator [26] as inspiration for our next concept. The resulting FSW profile concept is described further in the next section.

3.1.6 FSW Profile Concept

Based on the information received, a third concept in the cylindrical solution set was generated as illustrated in Figure 3.9a. The structure comprises of bent FSW panel modules assembled to a new concept with great potential for scaling and customer requirement adaptions. To illustrate the concept, the extruded profiles with T-bars were chosen as the stiffening element in the panels and for increased torsional strength cross-sectional beams were added to the design as seen in Figure 3.9b. The interface of the Hydro Panel Configurator is presented in Appendix E.2. Choices made concerning the panel length and width dimensions affect the possibilities within transportation methods. To avoid special transport and extra costs, the size limits for the panels are 2400mm×13000mm to fit on trailers. This limitation also is in accordance with stakeholder requirement 6 listed in Section 2.3.1.



(a) FSW panel concept.



(b) Stiffening structure.

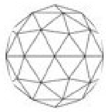
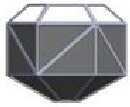
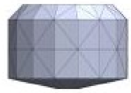
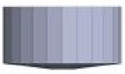
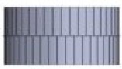
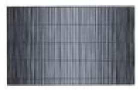
Figure 3.9: FSW panel concept based on available profiles from Hydro.

During the development phase, TechnipFMC asked for a design with other dimensions than first required to compare the solution with an ongoing development project of a GRP fish farm within the company. Refer to Appendix E for a presentation of the work carried out in this sub-project. Included in this sub-project is a cost estimate delivered by Hydro for the panels needed to build the structure walls. This estimate can be found in Appendix E.3.

3.1.7 Concept Evaluation

An evaluation of the presented concepts and learnings rounded off the work executed during the first development phase. Table 3.1 summarizes the discussed advantages and disadvantages of each concept. With learnings from the qualities of each concept, the FSW panel concept was generated and further developed to explore and verify its feasibility. Building on the experience and acquired knowledge from this chapter, a second development phase were initiated.

Table 3.1: Advantages and disadvantages of the structural alternatives.

			
Geodesic polyhedron	**6-sided prism**	**12-sided prism**	**16-sided prism**
✓ Modular ✓ Profiles and plates ✓ Structural rigidity ✓ Stress distribution ✓ Land-based transport	✓ Modular ✓ Profiles and plates ✓ Narrow top increases structural stiffness	✓ Modular ✓ Profiles and plates ✓ Land-based transport ✓ Approximation to cylinder	✓ Modular ✓ Profiles and plates ✓ Land based transport ✓ Approximation to cylinder ✓ Narrow top increases structural stiffness
✗ Many modules ✗ Complex joining ✗ Not a perfect sphere	✗ Large modules ✗ Complex joining ✗ Not a cylindrical shape ✗ Challenge to transport	✗ Complex joining ✗ A high amount of modules	✗ Complex joining ✗ A high amount of modules
			
24-sided prism	**Hollow profile cylinder**	**Mixed cylinder**	**FSW profile concept**
✓ Modular ✓ Few modules ✓ Extruded profiles ✓ Scalable ✓ Land-based transport ✓ Approximation to cylinder	✓ Modular ✓ Few modules ✓ Relatively high strength ✓ Scalable ✓ FSW ✓ Land-based transport	✓ Modular ✓ Few modules ✓ Profiles and plates ✓ Scalable ✓ FSW and bending ✓ Land-based transport ✓ Narrow top increases structural stiffness	✓ Modular ✓ Solid profiles ✓ Standard production ✓ FSW and bending ✓ Scalable
✗ Poor structural stiffness ✗ Requires new profile design ✗ Requires additional structure stiffening	✗ Additional stiffening ✗ Bending may negatively affect hollow profiles ✗ Hollow profiles increase the cost	✗ Complex joining ✗ Poor structural stiffness	✗ Requires additional stiffening ✗ Thin walls compared to the size

3.2 Development Phase 2

After the first development phase was concluded, it was clear that more focus should be allocated to the entire structural system in order to develop a feasible concept. The initial phase explored the general shape of the structure and mapped the available manufacturing methods. The next step was to divide the structure into different subsystems and explore different solutions for these. The interfaces between the different subsystems can then be investigated. This section will present the concept development process of the float collar and the bottom structure, before continuing development of the whole system. The concepts developed in this section are highly exploratory and consists of several different sets. This was done to quickly map the possible alternatives and challenges through discussion with leading experts and manufacturers. Through the continuous communication with TechnipFMC and experts in the field, the design space was narrowed, making further development more feasible.

3.2.1 Float Collar

In traditional open, flexible aquaculture systems the float collar usually consists of a polymer tube of relatively large diameter, attached in a circle around the fish pen. The polymer tube circle has a large volume, and creates buoyancy and stability to the net attached to it [61]. For closed, rigid structures the structure itself displaces water and creates buoyancy. The float collar then becomes more important to aid in stability of the structure, and create a platform for the additional infrastructure needed for closed aquaculture. Unlike net-based aquaculture pens, closed systems requires artificial internal currents, water circulation, waste management, and energy supply. This is required to implement the main functions described in Section 2.2. This means more equipment needs to be placed on or around the structure. In this paper the term *float collar* will be used about the entire part of the fish pen that is situated above the waterline, around the internal, closed, structure.

Three possible solutions for the placement of infrastructure were discussed:

- on the main structure and float collar;
- on external floating barges, or;
- connect the fish farm directly to a land-based facility.

Developing the system independent from land based facilities makes it adaptable to more localities along the coast line. To facilitate maintenance and keep costs down, the logical placement of this infrastructure is above the waterline, easily accessible on top of the float collar. In the aquaculture industry the common practice is to place fish farms relatively close to each other in a grid to facilitate efficient operation. This principle applies to closed fish farms as well, making it more efficient and sustainable with shared infrastructure and shared mooring. By locating common infrastructure such as power supply and food storage together, less infrastructure needs to be implemented to the fish pen itself, and supply logistics become simpler. In Figure 3.10 the principle is illustrated with six fish pens connected in a grid with shared infrastructure.

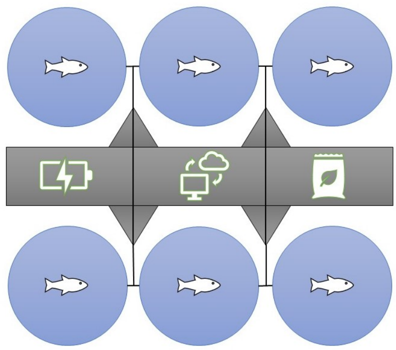


Figure 3.10: Fish farm grid with six fish pens connected to a infrastructure hub.

Since closed aquaculture systems requires artificial circulation of water, waste separation and control systems, they still require room for infrastructure on each pen. The float collar needs to be large enough to room the required infrastructure, and facilitate maintenance of the system. The shape of the float collar dictates how much room there is for infrastructure, how it can be manufactured, and how much resistance the structure creates for waves and currents.

General Shape

Figure 3.11 shows the initial shapes considered for floating collars. The illustration represents fish pens, in blue, with the attached floating collar in grey, viewed from above. The circular collar provides the lowest drag in water, but can be complex to manufacture in other materials than polymer because of the curvature. The square shape is simple to manufacture in aluminium, but creates the most resistance in water regarding waves and currents. The hexagon shape combines beneficial properties from both circular and square design, and was initially viewed as the most promising shape. The straight edges and symmetry makes it simple to manufacture, and it is closer to the circle regarding drag.

The octagon shape was later chosen for further explorations after a discussion with TechnipFMC and by looking to the industry. The increased amount of sides of a octagon reduces the length of the components, making transportation on road possible. The octagon is also the shape utilized in aluminium helidecks, making the use of existing knowledge and components possible.

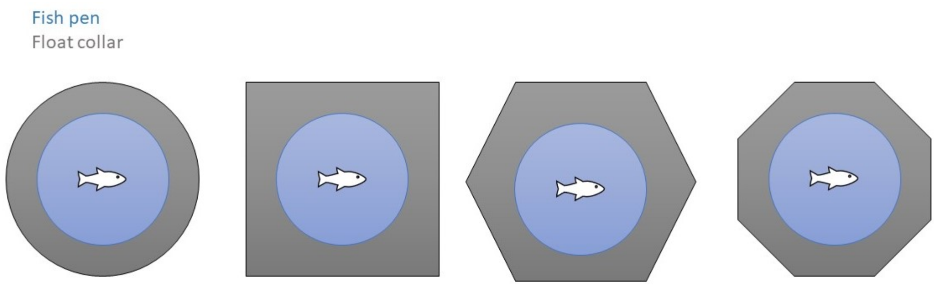
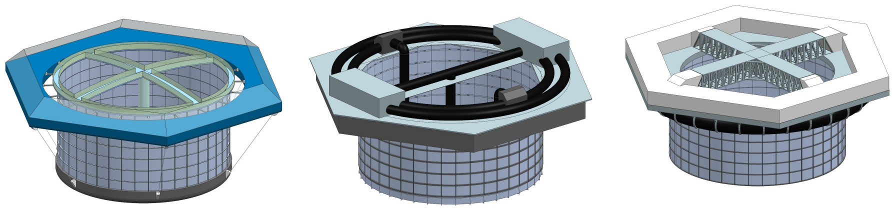


Figure 3.11: Shapes of floating collar.

Concept Exploration

Three concepts were made to illustrate possibilities in float collar design, and create discussion to uncover challenges. These concepts were made to collect initial thoughts of both the customer and leading experts, providing an important tool in quickly mapping challenges and important factors.

Figure 3.12a shows a floating collar connected with flexible mounts and wires, making the large weight of the fish pen dampened from the mooring and the waves. Figure 3.12b shows a rigid platform with square aluminium floating elements under. On top there are piping system and two control rooms to illustrate possible infrastructure. Figure 3.12c illustrates the same rigid platform, but utilizes a conventional polymer tube connected with hops under the hexagon platform. On this platform the infrastructure is sheltered from the elements and it includes two bridges cross the fish cage.

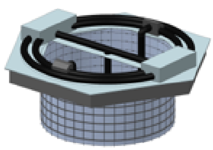
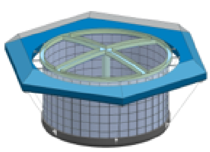


(a) Dynamic collar. **(b)** Rigid collar. **(c)** Rigid collar with polymer tubing.

Figure 3.12: Illustration of float collars and implementation of infrastructure.

The dynamic concept in Figure 3.12a was set aside due to the complexity involved with implementing infrastructure on moving structures, and the uncertainty of the benefits of a dynamic system. As the least promising solution, no further development was performed on this concept. A comparison between the dynamic and rigid collar solution sets is presented in Table 3.2. A rigid floating collar gives the possibility to implement the collar as a structural component, adding stiffness to the fish pen. It also facilitates implementation of the required infrastructure. TechnipFMC was positive to the concept with sheltered infrastructure, and suggested using aluminium modules often utilized in Norwegian offshore industry for control rooms and crew accommodation.

Table 3.2: Advantages and disadvantages of rigid and dynamic collars.

 **Rigid collar**	✓ Simpler solution ✓ Rigid structure increases stiffness ✓ Facilitates implementation of infrastructure ✗ Possibly less stable in waves
 **Dynamic collar**	✓ Possible benefits from dynamic dampening ✗ Complex solution ✗ Difficult to implement infrastructure due to movement ✗ Possibly more prone to fatigue and failure

Wave Slamming

Through discussion with Lader at the Department of Marine Technology at NTNU, wave slamming was quickly pointed out as a challenging factor. Wave slamming is when the structure moves vertically in the water and the structure has to *move away* the water. Consider an arrow piercing the water surface, because of its angled shape it cuts through the water. A cube on the other hand does not cut through the water and receives a significant impact force. Figure 3.13 shows three different cross-sections of the interface between the float collar and the sea.

The first interface on the left, which illustrates a polymer tube float collar, has an air-gap between the sea and the structure. This can create critical, sudden impact forces as the structure is submerged, and should be avoided. The second interface removes the air gap, but still creates significant resistance through the water. The third interface cuts through the water, and directs the forces inn towards the structure instead of straight up, minimizing the forces and momentum. [11]

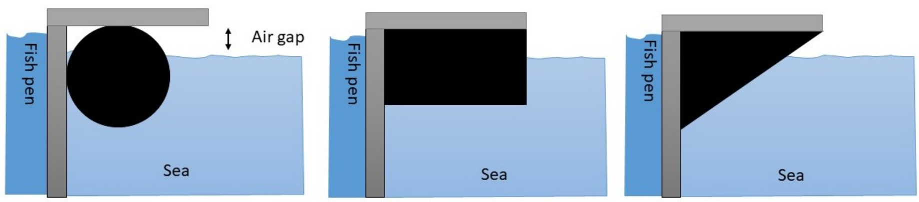


Figure 3.13: Wave slamming considerations

3.2.2 Wave Breaking System

Because of how responsive a closed, rigid aquaculture system is to both waves and currents compared to a net pen, the idea of implementing a wave breaking structure was discussed with TechnipFMC. The idea was a structure that could absorb the waves, reducing the global movement of the fish pen. This could be a system for individual fish pens, or it could be implemented around a grid of fish pens. As stated in Section 2.4.1, reducing the global movement of the fish pens would benefit the living conditions of the fish by reducing internal sloshing leading to stressful situations.

No concepts were developed for this idea because of uncertainty regarding the need of a wave breaking system. Wave breaking system is a subsystem that can be implemented later in the development, or in post-production if desired. Closed aquaculture systems are commonly localized in sheltered locations, and currents could for example be a larger problem than waves.

3.2.3 Bottom Structure Development

The bottom section of the fish pen connects the sides together, and is an important component regarding stiffness and strength of the structure. Being a large part of the structure, the design needs to facilitate simplicity in production and assembly. The bottom section also needs to facilitate waste collection to accommodate point 3 listed in Section 2.3.1. Because the fish excrement and food wastage dissolves in water it is challenging to separate it from the fluid. The stakeholder required a inclined bottom section to facilitate gathering of waste in the centre. The heavier waste particles are then forced outwards by the current, and will slide down the walls and gather at the bottom. Because of this, a smooth internal surface is required. Figure 3.14 illustrates a fish pen with inclined bottom and a internal circulation.

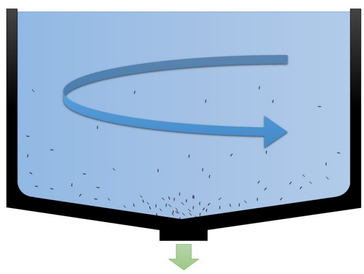


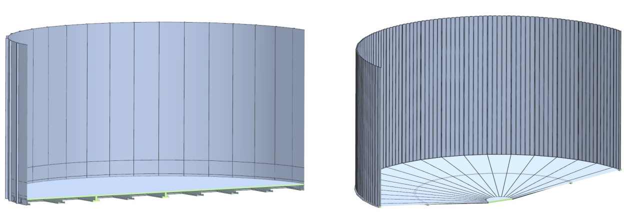
Figure 3.14: Inclined bottom to facilitate gathering of waste.

Two main sets of bottom structures were considered in this development phase. Modular bottom structures which combines aluminium profiles and panels to create a modular bottom section, and single part sections in either aluminium, GRP or concrete.

Modular Alternatives

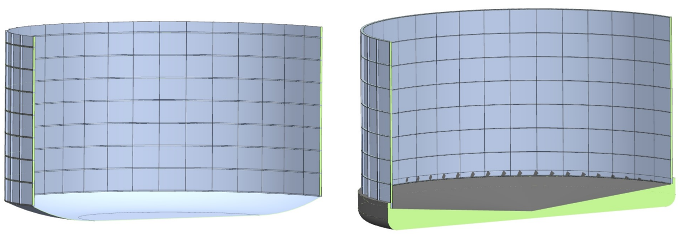
For the modular concepts, a similar structure as in the fish pen walls were considered; a combination of FSW panels and extruded profiles to enhance stiffness and modularity. Figure 3.15 shows two modular bottom concepts, one with a flat bottom and one with an inclined bottom. The flat bottom section, seen in Figure 3.15a, would need an additional internal structure to create an incline for waste collection.

This additional structure could be made of a cheaper material than aluminium to decrease costs and simplify the manufacturing process. The inclined structure in Figure 3.15b is assumed to be more complex to manufacture, but would not need an additional internal component. A method to manufacture the coned shape could be with circular sectors, tapering towards the centre, as shown in the figure.



(a) Flat bottom. **(b)** Inclined bottom.

Figure 3.15: Concepts in the modular bottom structure solution set.



(a) GRP bottom. **(b)** Concrete bottom.

Figure 3.16: Structures in the single-part concept solution set.

Single-Part Alternative

In order to explore the possibility of implementing structural components in other materials than aluminium, two single part bottom section concepts were developed and can be seen in Figure 3.16. Figure 3.16a shows a concept inspired from a typical pressure tank with a curved bottom section. This concept could be created with GRP and would require a mold. The advantages here are a light, and relatively stiff bottom section. It would however not be modular as a new mould would be required for every size of fish pen.

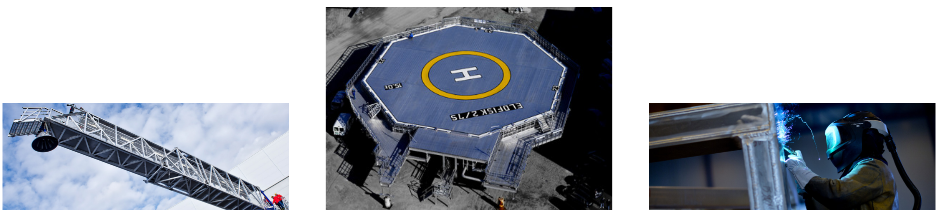
The same disadvantage abides for the concrete concept in Figure 3.16b. Theory concerning the behaviour of aluminium in contact with concrete and the need for isolation or sacrificial anodes to avoid corrosion are presented in Section 2.5.2.

The concrete bottom, unlike the aluminium and GRP concepts, represents a significant addition in weight. This could however add some stability to the structure by moving the center of gravity. A single part bottom section could also be made out of aluminium, as seen in pressure tanks, but at a larger scale. This solution was however deemed the least promising because of the specific equipment needed to produce such a part.

Knowledge and experience of concrete structures in marine applications are widely available, and TechnipFMC already has an ongoing project of a closed concrete aquaculture system. Because of this ongoing project, the concrete concept was not further investigated by us.

3.2.4 Concept Verification

After the FSW profiles were chosen, in corporation with Hydro, as the most promising construction component of the fish farm walls, another supplier of high-quality aluminium solutions was contacted: Marine Aluminium. Marine Aluminium is a leading supplier and constructor of offshore access solutions in aluminium. Figure 3.17 illustrates some of Marine Aluminium's products and areas of expertise: telescopic bridges, helidecks and aluminium welding. Their experience in construction of large structures for offshore utilization could be a major resource for further development, thus the aim of the meeting where to gather feedback, find inspiration for further design improvements and learn more about aluminium constructions in marine environments.



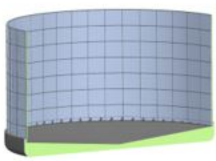
[9]

Figure 3.17: Marine Aluminium is a leading company in aluminium structures.

Together with our supervisor Ringen, we visited the company to discuss possible structure concepts, and share ideas and knowledge about partly and fully submerged aluminium structures. The CAD concept models generated were brought to the meeting to illustrate the current development stage. This was done to better be able to communicate and visualize the dissimilarities and characteristics of the ideas and to promote quick understanding of the project, as described in Section 1.4. The four main concepts discussed are illustrated in Appendix F.1 and are mainly characterized by their different float collars and bottom sections previously presented.

Showing the concept sketches to Midling and Kaalaas at Marine Aluminium initiated discussion around the different structural ideas. The main concept differences like the choice of material, choice of structure and implementation of existing products, were discussed and evaluated for further improvements. A summary of the pros and cons discussed during the meeting is presented in Table 3.3.

Table 3.3: Bottom structure feedback from the visit at Marine Aluminium.

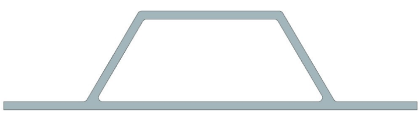
 **Flat bottom**	✓ Simple components ✓ Repeatable production and manufacturing method ✓ Modular and scalable ✓ Assumed to be cost efficient ✗ Requires additional structure on the inside for waste collection
 **Panel based bottom**	✓ Solution with internal incline for waste collection ✓ Modular ✓ Simple production ✗ Scaling requires new module dimensions
 **Single-part bottom**	✓ Solution with internal incline for waste collection ✓ Smooth internal and external surface ✗ Scaling requires new dimensions and change in production process ✗ Advanced manufacturing
 **Concrete bottom**	✓ Solution with internal incline for waste collection ✓ Lowers the centre of gravity ✓ Available in several given sizes ✗ Requires isolation to separate the aluminium and concrete section ✗ Scaling requires new dimensions and change in production process

The visit reinforced the importance of including manufacturing in the design. Seeing how their products were assembled highlighted the possibilities and limitations of design choices. The feasibility of the final concept is highly increasing by keeping the design and assembling process as simple as possible, the employees at Marine Aluminium stated.

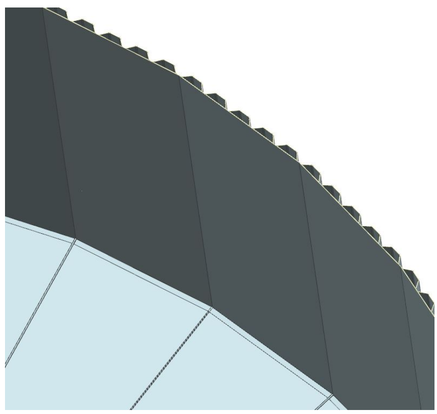
Important topics to focus on when designing:

- Straight sections simplifies the joining of two modules compared to bent sections.
- A simplified design often results in cost savings and a more attainable design solution.
- Hollow profiles reinforces a structure exposed to torsion.

Marine Aluminium advised utilizing smaller sections of straight panels instead of bending them to acquire a cylindrical shape. This idea combines the use of FSW panels and N-sided prisms, similar to the earlier generated concepts in Section 3.1. Assuming the panel width of 2.4m, which is the widest for transportation by road, a fish farm with 30m diameter would require at least 38 panels. In relation to a perfect cylindrical shape with 30m diameter, a 38-sided prism deviates by only 5cm radius. It is reasonable to assume that this is within tolerances for any sorting mechanism and approximately the same tolerances as the bent panels will achieve.



(a) Hollow profile advised from Marine Aluminium.



(b) Straight panels of hollow profiles.

Figure 3.18: Hollow FSW profiles advised by Marine Aluminium.

In addition they thought that utilizing hollow profiles, as illustrated in Figure 3.18, with higher torsional rigidity and strength could reduce the need for an additional stiffening structure, thus reducing weight and manual production. The hollow profiles could also introduce extra buoyancy because of the enclosed volume, affecting the stability of the structure. The design trade-offs between open or hollow profiles, and straight or bent panels are summarized in Table 3.4.

We were also given a tour around their fabrication workshops to learn about the facilities, processing methods and products. How the products seen on the tour inspired for further ideation is described in Section 3.2.6.

Table 3.4: Design trade-offs.

Open profile	**Hollow profile**	**Comment**
Easier to extrude Lower production costs Less material ->Lower material costs Additional stiffening structure increases costs and weight	More challenging to extrude Higher production costs More material ->Higher material costs and weight Higher profile stiffness Additional buoyancy from the hollow volume	An open profile is easier to develop and cheaper to produce, this results in decreased costs. On the other hand, the increased torsional stiffness of hollow profiles may reduce the need for additional stiffness.

Straight panels	**Bent panels**	**Comment**
The 2.4m wide panels fits trailer transportation limitations Easier to handle Fewer production steps 38 panels give 5cm deviation form a Ø30m cylinder Support structure made of straight profiles simplifies the assembly	Must be bent at the assembly location Can utilize FSW to create wide sections before bending, >10m Require bending for panels and additional stiffening structure The additional production steps are time consuming and increase costs	Employees at Marine Aluminium called attention to the simplified manufacturing and assembling of the structure if the panels are straight.

3.2.5 Inspiration from Kapp Aluminium

On behalf of the project, Høgberget visited the local company Kapp Aluminium to learn more about their products and experience within marine constructions in aluminium. The purpose of the meeting was to initiate dialogue for further cooperation and knowledge sharing, and to learn from their welding and construction experience. The company also is an potential collaborator for assembling of the aluminium fish farms at a later point of the project.

Kapp Aluminium's ability to assemble large structures rapidly, as the helideck seen in Figure 3.19, was an inspiration for the further development. The building of such structures is finalized in three weeks only, when the material is delivered in packages ready to assemble. Generating a corresponding structure with equally low assembly time and smart solution architecture should be a goal for the aquaculture structure.

Figure 3.19: Aluminium profiles in a helideck made by Kapp Aluminium.

3.2.6 External Structure

In dialogue with Midling, Kaalaas, Lader and Tryland, a concern was voiced regarding the stiffness of the structure. The common concern was that the structure could be susceptible to fatigue fracture unless sufficient stiffness was ensured. As described in Section 3.2.4 Marine Aluminium recommended looking at the use of hollow profiles to increase the strength. After visiting Marine Aluminium's production plant and through discussion with Høgberget in TechnipFMC the idea of implementing an external structure was generated. Without strength analysis, it is difficult to tell if a chosen design is strong enough. The idea of an external structure was to ensure stiffness by smart design. The dimensions of the structural members could then be decided once a clearer image of the load cases are generated.

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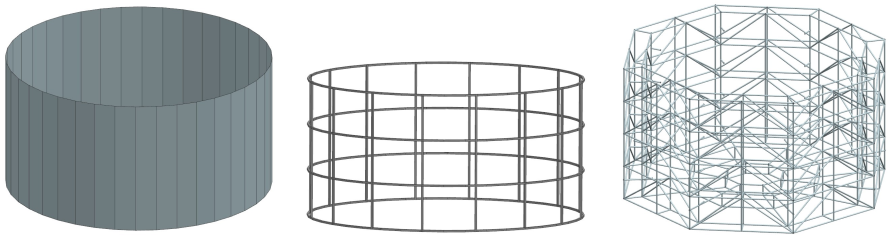
Figure 3.20: Aluminium stair tower for offshore installations.

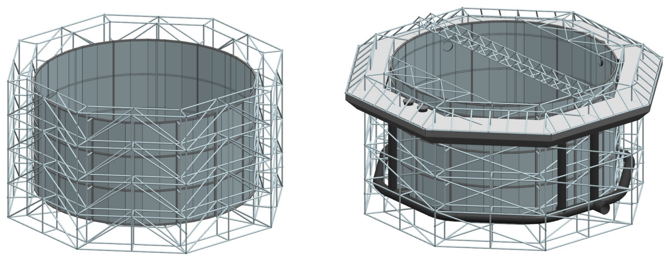
Taking inspiration from the aluminium stair towers produced by Marine Aluminium, see Figure 3.20, a concept with an external structure was generated with focus on repeatable assembly. Figure 3.21 illustrates the principle of combining the internal FSW structure with stiffening profiles and the addition of an external structure. This makes it possible to utilize existing components and experience from the offshore industry to increase structural stiffness. The concept started as a way to explore the design alternatives to assure significant stiffness. As no calculations are done, the need for an external structure regarding stiffness is not verified.



(a) FSW panels. **(b)** Stiffening profiles. **(c)** External structure.

Figure 3.21: Proposed improvements to increase structural strength.

Figure 3.22 illustrates both the stiffening structure and a more complete concept based on an internal structure of FSW panels, an external structure implemented with a float collar, and a circulation system integrated within the external structure. This concept utilizes 40 straight sections of FSW panels, as recommended by Marine Aluminium. The internal structure is therefore almost cylindrical, and the FSW panels can be transported by road. The octagon external structure also achieves this, with no components over the transportation limit. Utilizing a 40-sided prism and an 8-sided float collar makes the design symmetrical and promotes modularity.



(a) Strengthened concept. **(b)** More comprehensive concept.

Figure 3.22: Concept with external structure, float collar and circulation systems.

External Structure Evaluation
Possibilities and challenges related to the additional structure are summarized in Table 3.5. The possibilities and challenges of this concept will be more thoroughly discussed in Chapter 4.

Table 3.5: List of the possibilities and challenges with an external structure.

Possibilities	**Challenges**
Facilitates manufacturing and assembly.	Fouling $\rightarrow$ Hard to clean.
Self carrying.	Trash and driftwood can get stuck.
Simple components.	Can increase weight.
Utilizes existing solutions.	Increases resistance to current and waves.
Facilitates connection of pipes and implementation of infrastructure.	
Creates a protective cage around pipes and other infrastructure.	
Can increase hydrodynamic dampening.	

Modularity
This final concept iteration is developed with a focus on modularity and reducing assembly cost to make the design economically feasible. On request from TechnipFMC several figures were made to illustrate the modularity and a possible assembly process of the structure. To highlight the alternatives, Figure 3.23 was created.

The figures illustrates how the external structure can be assembled vertically from the bottom and up to create a robust platform for the remaining structure. No details of joining methods are illustrated in the concepts, as they will depend on the final design and strength requirements. Similar joining methods of extruded profiles and welded joints used in the aluminium helidecks by Kapp Aliminium are also here a possibility.

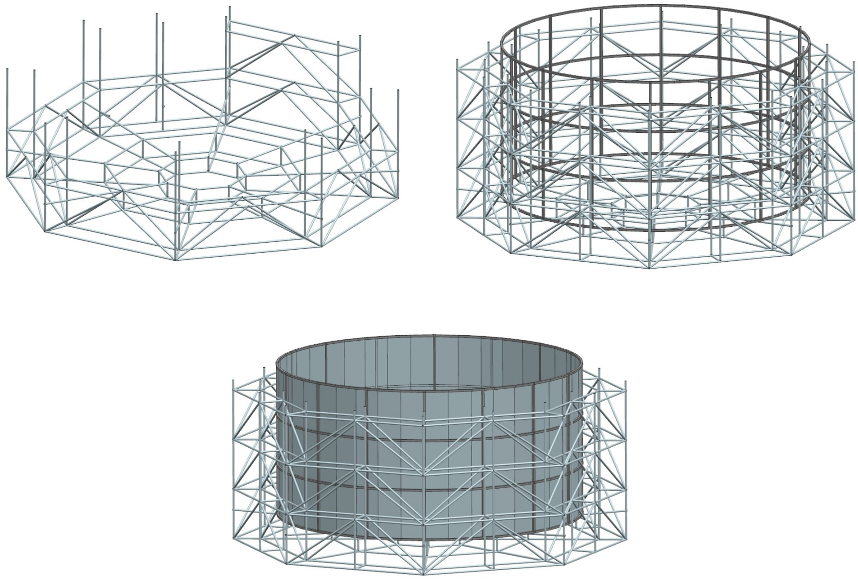


Figure 3.23: Illustrated modular assembly procedure.

Figure 3.24 illustrates how different sections of FSW panels can be customized to fit a larger range of individuality of customer demands to suit particular requests. Alternatives in infrastructure and interacting components such as piping or connections to transfer biomass can all influence what the customer require from their supplier. These modular solutions aim to accommodate large external variance and internal standardization in TechnipFMC, which is in accordance with the theory presented in Section 2.8.

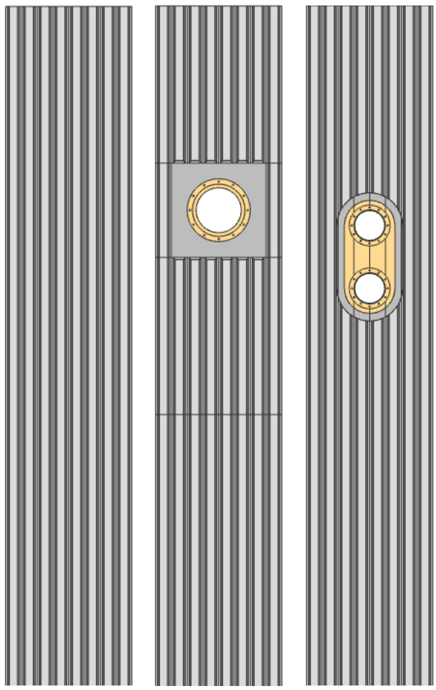


Figure 3.24: FSW panels with implemented connections for tubing systems.

Chapter 4

Discussion

This chapter will systematically go through the entire thesis and discuss the methodology used, the literature studies, the results and the collaboration done throughout this project. The discussion will refer to the research objectives stated in the beginning of this thesis and argument on how this project achieved its predetermined goals.

Methodology

The exploratory set-based development methodology utilized in this project suited the outlined scope as the focus was to generate several concepts and evaluate possible solution sets, this in accordance with point 9 listed in Section 1.2.2. The use of continuous dialogue and visual CAD models have been a key factor in the ability to communicate well with each other and a wide selection of leading experts. Through early, extensive research, it was made possible to clarify the scope of the solution space including the investigation of several standards and regulations, research about experience with aluminium in marine applications and cost reducing production methods. With a small development team, it has not been possible to go into depth of all the concept alternatives or even discover all the options. Still, the studies have covered a wide area of interest. As this project has focused on communication with both experts and employees from the industry, there is some assurance that the critical design factors have been included.

Conducting parallel development of alternative solutions within each set challenged our two-person team to work structured, both independent and together. Due to the comprehensive scope of the system and industry, a structured approach was necessary to not get overwhelmed and confused. Looking at the system as several manageable sets instead of one complex structure was strategic to simplify the problem. Allowing for independent work seemed to increase the generation of new ideas and encourage innovative thinking as inspiration occurred at all hours, not only when dedicating time for the project. On the other hand, the greatest ideation happened when sharing thoughts, ideas and knowledge to bring the concepts further. By discussing all ideas and contributing with new thoughts, the concepts were developed further in collaboration before presented to external parties.

The sought out contact network and focus on visual communication has been an incentive to achieve progress in the project. The meetings then became small stage-gates where new models were discussed before developed further. The development method of set-based concurrent engineering with a focus on rapid generation of concepts has proven an efficient mindset to identify critical factors quickly, and the 3 principles of SBCE also helped to guide the development in this project. Similar projects with a high level of initial uncertainty could in our opinion benefit from this method, as it efficiently sorts the information provided by the contact network and delays critical decisions until a sufficient amount of facts are gathered.

The set-based development methodology were in this project utilized as a tool to promote wide exploring of different concepts, and to avoid locking the project to the first promising solution. As this project was conducted in the very early concept development phase, mapping the design domain and identifying the scope of possible solutions were more important than generating a single detailed design. The practice of trade-off curves used in both set-based and DFM methodologies has been a useful tool to categorize solutions, but has proved difficult in early concept development because of the high level of uncertainty. To create thorough trade-off curves, both research and testing are necessary, requiring significant time and resources. Utilizing rapid concept development to communicate solutions and quickly map the possibilities and challenges were a more suited method to this project. If however TechnipFMC are to take this project further, they can rely more on their resources and create detailed trade-off analyses to guide their decisions.

The methodology utilized in this thesis is a combination of more than one methodology. In small independent development projects as this one, the methodology used must be tailored to the scope and complexity of the project. Less complex and more certain projects would not need the same focus on research and exploration, and could be more result driven. A larger development team with more resources could go further into detail on the alternative solutions, possibly discovering flaws and great potentials earlier. However, the methodology utilized in this thesis suited the scope of the project and was efficient in developing an initial foundation for further development, achieving the research objective for this thesis.

Literature Studies

The literature studies were performed in accordance with point 1-8 listed in Section 1.2.2 to create the best possible foundation for ideation and development. Because of the newness of closed, floating aquaculture systems, the literature study had to be conducted at a general level starting with a definition of fish farm classifications and an overview of the main functions and contributors to define the system. These initial sections introduce the desirable characteristics of a closed system that is not achieved by the traditional net pen. Advantageous factors include the opportunity to control the water quality, and the possibility to prohibit fish lice, fish escapes, contamination of the seabed and emissions from chemicals used to control fish lice. The environmental and fish welfare benefits of closed cages compared to open net pens are present, but at the sacrifice of increasing costs and need for new technology.

The listed requirements, standards and regulations previously described are mainly focusing on the traditional widespread net pen usage and offshore industry in Norway. The newness of closed aquaculture systems may be the reason for the lagging recommendations and requirements. The acquired information is assumed to serve as relevant guidelines to what future standards and regulation may contain, making sure the development is robust, safe and feasible. Applying for a licence to either develop or operate a fish farm is very strict, making the cited papers highly relevant for further project work.

SINTEF's ongoing research on the hydrodynamic behaviour of closed fish farm systems is vital for this project, as they are close to the only publicly available resource on this subject. Through dialogue with Kristiansen at SINTEF Ocean, a rough understanding of the topic is acquired, but further research and documentation are recommended to fully understand its extent. The theory of hydrodynamic behaviour and load combinations are incredibly complex and crucial for further development. In this project, it is beyond the competence and available resources of our two-person team to investigate the subject in detail. A more multidisciplinary team is recommended to better understand the complex hydrodynamic load case and accordingly set the structural dimensions.

The knowledge and production methods of aluminium is highly available in the Norwegian industry. Implementing them to construct a *functioning* closed aquaculture system is readily achievable, implementing them to construct a system that is *cost efficient* and *sustainable* requires further research and development. There is experience with offshore structures in aluminium, and regulations and standards for designing and constructing these. These structures does not however require to contain an internal water volume with living fish which might complicate the situation with its strict requirements to internal water quality. There also exists little experience with the use of aluminium in aquaculture systems and how fouling and corrosion behaves in this application. Further research is required to validate the utilization of aluminium and the requirements for corrosion protection and surface treatment. At this point, no critical aspects have been detected, nor have any contacts advised against the implementation of aluminium in fish farms during this project.

At one point, the wish for comprehensive testing of the system became relevant for further learnings and assessment of the structural behaviour in the water. Section 2.7 in the literature studies comprises the scaling theory. In accordance with the statements written by DNV-GL, the need for model tests increase as no simulation software includes all the existing load components. Conducting valid model tests are both comprehensive and time-consuming. After dialogue with Lader and later Ringen, the model testing was out of the question due to the limited time frame and resources. Despite this, performing model tests are highly relevant to test the system and should be planned and executed by TechnipFMC as soon as possible. Interpreting test results are time-consuming and require a strict procedure to give relevant information. The lack of simulation programs comprising the unique load case of floating closed aquaculture systems supports the need for model tests at an early development stage to understand all aspects of the system. With this in mind, the literature studies about scaling theory seem very relevant for further use of this project. The topic is included to highlight its importance and aid further development teams

The research objective states the request for a modular project solution. To understand the theory behind modular concept development, Section 2.8 introduces the purpose of aiming for modularity. As TechnipFMC expects a wide range of individuality of customer demands, a modular system is desirable to cover a broader market segment. Developing a modular system can also include repeatable manufacturing methods and processes which contribute to desirable cost savings for the company. Aiming for a modular solution is strongly supported by Midling and Kaalaas to maintain a cost-efficient design. The mindset of modular product development worked as an inspirational way of thinking throughout the development phases.

Results

The Morphological Chart, Figure 3.2, used in this project has proven to be a key driver in the initial development phase. When generating new ideas and concepts based on the alternative means, the method was advantageous. However, to establish a common understanding of the combinations, the need for visual sketches and drawings appeared. Showing someone a model of the concept instead of using words and phrases to explain the design, quickly established a common view and understanding among the involved parties. A common understanding improves the discussion, detection of challenges and opportunities for later improvements. Implementing the method helped to broaden the solution space and increase the concept variation by the generation of several alternatives for each solution set investigated.

Weekly status meetings with employees at TechnipFMC were conducted to follow up on the work conducted at both at NTNU and internally in the company. As the development of sub-systems happened simultaneously inside and on behalf of the company, the need for being up to date was crucial to avoid misunderstandings and late information. On the other hand, the risk of early favouring one concept over the others increases when exposed to positive and negative feedback before equally investigating several ideas within a solution set. Staying within the mindset of SBCE required reflective examination of the reasons and facts behind each decision and courage to postpone a decision if the necessary information lacked. Also, in situations where one or both of us became attached to a specific concept, honest and clarifying dialogue helped to get back on track with an open mind to all the ideas.

The contact with external companies and experienced workers brought in a new drive, more knowledge and facts to the development process. Without the knowledge from the Profile Academy at Hydro and the tour around Marine Aluminium's facilities, the acquirement of basic aluminium construction knowledge would have taken much longer and lacked the transfer of experience we got. Learning from external parties helped to look at the project from new perspectives and evaluate the resulting work at different levels; from a manufacturing point of view, cost-oriented point of view and feasibility point of view. Especially Midling and Kaalaas pointed out the importance of a simple design with realizable solutions for the concept to have a chance of being built in the future. The work executed after this meeting aims to incorporate this discussed simplicity, as we share their perspective.

Towards the end of the last concept development phase, a discussion about the dimensioning requirement was initiated by Tryland, a Senior Scientist at SINTEF Manufacturing. In his opinion, strength analysis of the concept are necessary to validate whether or not aluminium is a competitive material choice compared to concrete and GRP. With the dimensioning load, the amount of material and associated production cost can be estimated and further development rejected or continued. The scope of this project does not comprise detailed engineering of the concepts, as investigating the closed fish farm industry and the opportunity to introduce aluminium is the main goals. But with this foundation of information, the investigation of structural strength should be of interest for further and more detailed work.

Final Concept Iteration

The final concept iteration done in this thesis combines an internal structure of straight FSW panels with a rigid external structure of extruded profiles. This concept focuses heavily on modularity and assembly to meet the tenth objective task listed in Section 1.2.2: Generate and develop a closed fish farming concept in aluminium based on the most reliable findings.

There are both possibilities and challenges with the final concept iteration. The use of straight sections require more connections between components than bent sections. Take the example of 2.4m wide FSW panels, every 2.4 meter both the FSW panels and the stiffening structure would need to be welded at an angle, or joined in another fashion, to the next section. Curved panels on the other hand require curved stiffening sections. These curved section have the same curvature as the diameter of the fish farm, longer sections can therefore be manufactured and bent to facilitate less manual joining. Whether or not the cost of bending both FSW panels and the stiffening structure are higher than having to join individual straight sections need to be investigated. Simplifying the design to accommodate the production methods readily available and the experience available with aluminium joining could result in cost savings. These design choices affects not just manufacturing and assembly, but where it can be manufactured and how it can be transported. All important factors affecting whether the product is economically sustainable or not.

All the earlier concepts presented would require significant preparations and construction of scaffolding to both manufacture and transport the fish pen. If the required scaffolding to construct the system could be implemented to the system itself as an external structure, it could create a self carrying system which facilitates manufacturing and transportation. The components and construction methods are well known, and can be implemented without much alteration. The external structure would make attaching piping and infrastructure more manageable, and provide a protective cage around the equipment. The structure could also provide stability to the fish pen by adding resistance to movement through water, hydrodynamic dampening. This however also means increased resistance to current. Because the degree of fouling is uncertain, the intricate structure may be too hard to keep clean from fouling. A concern raised at a meeting was that trash and driftwood would get stuck in the open structure, and outer shielding would be required.

Through research, continuous concept development, and communication with experts and industry, the possibility of introducing aluminium as a new, sustainable and reliable building material to the fish farming industry is demonstrated and validated in this thesis. This is in accordance to the research objective of this thesis. Further research, development and validation is now necessary to go from possibility to reality.

Collaboration and Validation
The communication network provided by supervisor Ringen, TechnipFMC and internally at NTNU has been an essential resource in this project. The experts and companies consulted have been fundamental for the design paths and choices made. A major part of the consultation has come from experts and companies working within the aluminium industry, which has helped to base the design choices on experience and well-founded argumentation, but at the risk of biased opinions. The evaluations and choices made regarding the alternatives presented in each solution set are based on the feedback and information gathered from the contact network and literature studies. All information is documented for readers to verify the validity of the work. As the outcome of the case study is partly dependent on the information given by the external contacts, the reproducibility is uncertain. On the other hand, several independent contacts have contributed to the project to increase the validity of the findings. Further communication and consultation is recommended to focus on an even broader perspective and several experienced contacts to assure an objective consultation on the design.

TechnipFMC has been an engaged collaborator throughout the entire project, and has been a driving force for the project with weekly meetings and feedback on the concept ideas presented. Their design basis for a concrete fish farm was a good help in mapping the main functions and requirements for this project and worked as reference for some of the headings in the study of standards and regulations. An increased focus on knowledge and lessons learned from their aquaculture projects to this project could have pushed the design process further by reducing the need for literature studies in this thesis. A closer collaboration with relevant employees from their previous closed fish farm project could have enhanced this work by pushing the development to a more detailed level.

Chapter 5

Conclusion and Further Work

This master thesis project was conducted to investigate and develop possible aluminium concepts of sustainable and modular closed fish farms. The project was carried out by utilizing a customized set-based development methodology with focus on mapping the solution space through a broad literature study and knowledge gathering. Inspiration from the well known Set-Based Concurrent Engineering and Design for X methodologies was used to structure the work and promote good communication and collaboration within our two-person team. The development focused early on mapping the design domain thoroughly to better understand the extent of the closed aquacultural industry and the opportunities within aluminium construction rather than risking poor design decisions in the early development phase. Rapid concept generation was performed to visualize the alternative solutions and promote communication throughout the project. Experienced workers within the affected industry of this project have been sought out to validate the findings and generated closed fish farm concepts.

Narrowing down the solution space by rejecting the least feasible ideas resulted in a concept based on FSW panels with an external stiffening structure inspired by the shipbuilding and offshore industry. This concept utilizes 40 straight sections of FSW panels and an 8-sided float collar to make the design symmetrical. The resulting concept highly accommodates modularity and scalability, together with well-known manufacturing and assembly methods for aluminium to minimize costs. Several aspects of the concept are still uncertain and require further research and development.

The work presented can be considered as a wide-ranging foundation for concept development of a floating closed fish farm in aluminium, including both the findings from the extensive literature study in Chapter 2 and the results from the development phases in Chapter 3. This achievement corresponds to the outlined main purpose of this thesis presented in Section 1.2. Our interpretation of the set-based product development methodology combined with rapid concept development and focus on design for manufacturing proved an efficient method for wide exploration for a complex system with high initial uncertainty. We believe similar development projects can benefit from the experience generated through this project by also focusing on visual communication to quickly map the feasible solutions and delay decisions until sufficient knowledge is gathered.

There is a lot of possibilities in further work to improve the final product, gather more knowledge and execute tests and simulations to validate the reliability of the structure. There should be conducted model tests where the scaling is as accurate as possible to achieve relevant design data, further research the hydrodynamic load case and increase knowledge of the interaction between the sea loads and the structural response. Both the external forces from waves, current and wind, and the internal forces from the moving water volume needs to be understood and categorized in order to create a feasible design. With the load scenario at hand, the structure dimensions can be determined and used to estimate the project costs. Whether or not aluminium is an economically competitive material for the closed fish farming industry can then be validated.

As part of the detailed design decisions, a thorough analysis of connection methods should be performed. Different concept designs results in different load scenarios and load distributions, and the joining method of structural members needs to be optimized for strength, weight, price and manufacturability. Some joining alternatives are presented previously in the thesis, but no final decisions were made. Further and close communication with an experienced manufacturer should be implemented to ensure a feasible design.

With the natural oscillating behaviour of sea which is a repeating load cycle, fatigue damages in the structure and mooring system should be evaluated. This is not included in this paper, but is considered to be essential for the robustness and lifetime of the system. Further research and testing should also be performed on corrosion and fouling of aluminium in aquaculture applications.

A more multidisciplinary development team or closer collaboration with external contacts should be implemented to assure the verification of the design choices done in this project. More experience from the marine industry can be taken into consideration to ensure a seaworthy final design with good integrity and reliable solutions. Biologist and experienced fish farmers should be involved to ensure that fish health and welfare are prioritized correctly, and that the final solution promotes optimal growth conditions for the fish stock. With the increasing focus on environmental sustainability, the environmental impact should be minimized in all life cycle stages and should be considered as essential.

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Appendix A

Development Licences

A.1 Existing and Upcoming Concepts

Table A.1: Development licences at the Department of Fisheries.

Company	Fish-Farm Name	License appl.	MTB	Shape	Material	Concept	Dimensions	Application Status
Hydra Salmon Company[67]	Produksjonstank	4	3 120	Cylinder basin	Steel and metal/plastic net	Semi-closed light regulated production tank	Ø 60m Located 20m BSL	Accepted
Marine Harvest, developed by ØPD[37]	Donut	8	6 249	Torus	HDRP	Closed unit	Ø 54.5m Length 171 m Height 16.5m Vol. 22 000m^3 Flow 22 000m^3/h 200 000 fish/unit	Ongoing clarifications
Lerøy Seafood Group[5][62]	Pipefarm	9	7 020	Pipe		Closed floating current pool Water intake at 30-35m	Vol. 2×3000m^3 Preline 50% scale: Length 50m With 12m Depth 8m	Ongoing clarifications
Stadion Laks[38]	Stadion-bassenget	15	11 700	Halfpipe	Reinforced concrete w. integrated floating chambers	Semi-closed floating pool Water intake at 20-35m	Vol. 34 000m^3	Ongoing clarifications
Fishglobe AS[16][23]	FishGLOBE	3	2 340	Sphere	PE	Closed cage technology	Vol. 3 500m^3 Ø/height 19m	Ongoing clarifications
Wenberg Fiskeoppdrett and Edelfarm[8]		10	7 800	Cylinder	Concrete	Semi-closed module based technology	Vol. 3 000m^3	Aviating evaluation
Sustainable Salmon[25]	Lukka Landnot	8	6 240	Cone	Concrete Float collar Net cage with lining	Closed Rails in concrete costr. used for sliding out net	Vol. 249 000m^3 Ø 124m	Aviating evaluation
Aquantum Leap AS (Nutreco and Seafarming Syatems)[24]	Aquantum 12K Aquantum 500K	24	18 720	Cylinder	Steel	Closed unit	Vol. 12 000m^3 and 500 000m^3	Aviating evaluation
NSF	Green Seafarm	12	9 360			Closed system for salom farming		Aviating evaluation
Marad Norway[7]	Tours Seafarm	2	1 560	Cylinder	Steel	Closed scalable unit, built at hipyard	Shipyard capacity is the limit	Aviating evaluation
Måsøval Fiskeoppdrett[6]	Aqua Semi	5	3 900	Cylinder	Steel Steel grid floor	Partly submerged, semi-closed unit	Vol. 75 000m^3 Floating units at 25m BSL Height 20-25m	Aviating evaluation
Tombre Fiskeanlegg/ Smart Flex[63]	Semi Torus	6	4 680	Torus	HDPE	Floating scalable closed unit	Vol. 16 000m^3 Scalable between 10m^3 and 100 000m^3 Ø 16m Torus length 138m	Aviating evaluation

[28]

Appendix B

Regulations and Standards

B.1 Requirements Associated to Fish Welfare

Operational Requirements
Withdrawn from regulation /002a/ [17]:

- Operations shall be technical, biological and environmentally defensible.
- Aquaculture farming with species not naturally occurring in the area is forbidden.
- All operations should promote fish health and welfare.

Processing Plant Requirements
Withdrawn from regulation /002a/ [17]:

- Installations and the processing unit shall
  - promote movement and other natural behaviour.
  - not contain sharp edges or objects or be made of harming material to the fish.
  - cause minimal risk of hazardous events resulting in injuries and stress.
  - promote inspections of the fish.
  - promote caring and treating of infected individuals.
- Processing and maintenance of the processing unit and its coherent installations shall aid protecting the fish from attacking predators.

Fish Handling Requirements
Withdrawn from regulation /002a/ and /002b/ [17] [18]:

- Fish shall be farmed in environments that provide optimal conditions and protects the fish from harmful situations and unnecessary stress. Never transfer fish to harmful aquaculture cages with disease outbreaks that may infect the individual.

- To promote good fish welfare, sort and separate fish with respect to size when necessary. [...]

- Do not unnecessarily handle the fish. Handling, including vaccination, sorting, hand netting and pumping, shall be performed carefully and in a defensible tempo to avoid harmful situations and unnecessary stress. Minimize handling of fish outside of the water.

- Minimize the pumping distance. While pumping fish shall height, pressure and drop be design to avoid hazardous situations.

- Proper water quality is a requirement while handling fish, the quality properties shall be based on the fish species. Oxygen saturation shall be monitored while sorting the fish. An exception is made if the sorting lasts less than 30 minutes in water temperatures below $6°C$. Immediately implement necessary efforts to ensure good fish welfare if behavioural changes is observed while handled.

- Account for fish welfare and health when giving vaccines, this includes accounting for the risk of infection, fish size and growth rate, evolution, water temperature and time of vaccination.

Feeding Requirements
Withdrawn from regulation /002a/ [17]:

- Feeding quantity and quality shall promote good health and fish welfare. Feed according to species, age, evolution, mass and both physiological and behavioral needs.

- Normally, feed the fish on a daily basis unless not expedient for the chosen species or specific evolution period. Feeding method shall easily access the food to the whole stock without any risks of hazardous events.

- No feeding must occur if undesirable according to fish welfare, hygiene or quality. Minimize the feeding period.

Stocking Density Requirements
Withdrawn from regulation /002b/ [18]:

- Stocking density shall be customized relative to water quality, physiological and behavioral needs of the species, health, farming method and feeding technology.
- Stocking density per production unit with fish of salmon and rainbow trout shall never exceed 25 kg/m^3, with exception of butchering cages. Calculations of stocking density shall account for the movement volume of the fish.

Water Quality Requirements
Withdrawn from regulation /002b/ [18]:

- Water volume, water quality, water circulation and current shall promote optimal living conditions for the specific fish species, age, evolution, mass and both physiological and behavioral needs.
- Water quality and parameter interactions shall be monitored based on the risk of poor fish welfare. Oxygen saturation and temperature among other significant parameters to fish welfare shall systematically be monitored.

B.2 Load and Load Combinations

The following information is withdrawn from NS 9415 [42].
Permanent Loads
Loads which will not be removed during the design working life:

- the weight of the marine fish farm in the air, including permanent ballast;
- the weight of fixed equipment, which cannot, or shall not, be removed;
- static buoyancy forces.

Variable Function Loads
Maximum loads which can be removed or relocated:

- mechanical, movable equipment;
- personnel;
- stored goods, such as feed;
- variable ballast;
- mutual load between main components, such as floating collar and raft;
- normal boat impact, fendering and mooring of adjacent floating units;
- movable parts, as well as extra loads, applied as a result of certain work operations.

Deformation Loads
Loads which occur at forced deformation:

- pre-tensioning;
- mooring;
- temperature.

Environmental Loads
Loads which are applied by environmental circumstances;

- wind;
- waves;
- current;

- ice.

Accidental Loads
Accidental/damage conditions shall be calculated, assessed and documented, and the impact of them shall be evaluated:

- breaks in mooring lines;
- puncturing, disappearance or loss of floating parts.

Appendix C

Aluminium Alloys

C.1 Aluminium Alloys and Tempering Designation System

Table C.1: Strain hardening and heat treatment notations with description.

[65]

Strain hardening notation	Description
H1	Strain hardened only
H2	Strain hardened and partially annealed
H3	Strain hardened and stabilized
H4	Strain hardened and lacquered or painted
HX2	Quarter hard
HX4	Half hard
HX6	Three-quarters hard
HX8	Full hard
HX9	Extra hard

Heat treatment notation	Description
T1	Naturally aged after cooling from an elevated temperature shaping process, such as extruding
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3	Solution heat treated, cold worked and naturally aged.
T4	Solution heat treated and naturally aged.
T5	Artificially aged after cooling from an elevated temperature shaping process.
T6	Solution heat treated and artificially aged.
T7	Solution heat treated and stabilized (overaged).
T8	Solution heat treated, cold worked and artificially aged.
T9	Solution heat treated, artificially aged and cold worked.
T10	Cold worked after cooling from an elevated temperature shaping process and then artificially aged.

Appendix D

Design Considerations

D.1 Effects of Design On Corrosion

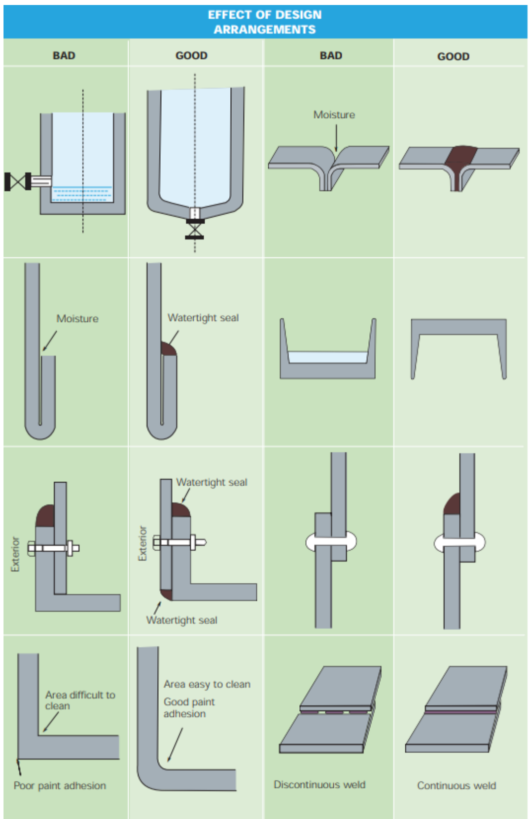


Figure D.1: Design considerations to minimize corrosion. [59]

Appendix E

Sub-project

E.1 New Dimension Requirements

A request from TechnipFMC initiated a sub-project for the development of a FSW panel concept with new dimensions. Table E.1 presents the desired measurements for the diameter and height of the construction. The reason for this sub-project was to create a cost and weight estimate for comparison to their ongoing development project of a GRP construction. If the aluminium construction already at an early point stood out as less economical and feasible, the project would be discarded.

Project	Diameter [m]	Depth [m]
Ongoing project	30	15
Sub-project	20	26

Table E.1: Dimension requirements for ongoing project and sub-project.

The concept was modelled in SolidWorks with assigned material properties according to the values in Table 2.3 to obtain a weight estimate. Changing the dimensions put the concept through a scaling test, which turned out to be quite simple with simple changes in the curvature and panel length. This demonstrates the advantages of a modular design and the possibility to cover a wide market segment with different size requirements. The resulting design is illustrated in Figure E.1

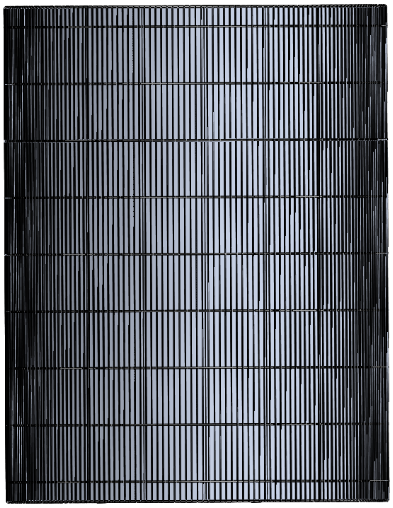
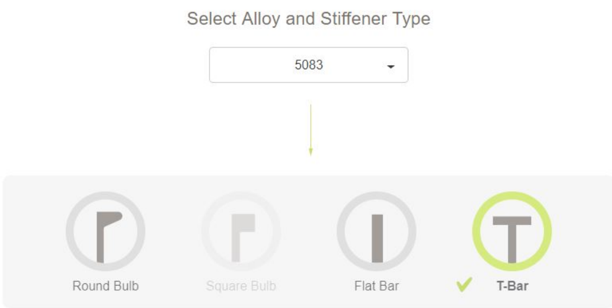


Figure E.1: Concept presented for the sub-project.

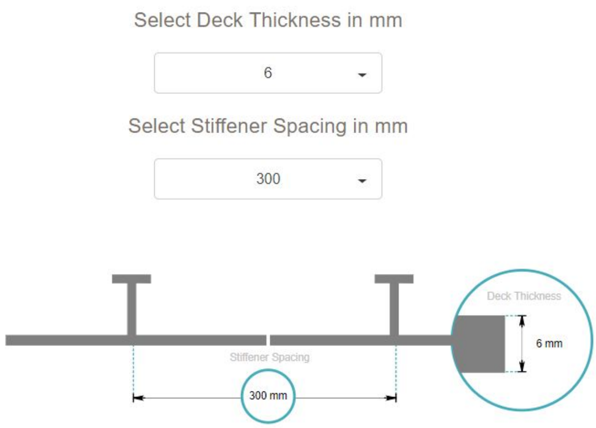
The parallel project at TechnipFMC that investigates the implementation of other materials as the construction material, was not part of the extent of this thesis. No further development of the structure from the sub-project in the pre-study is performed as part of the thesis.

E.2 FSW Profiles for Cost Estimate



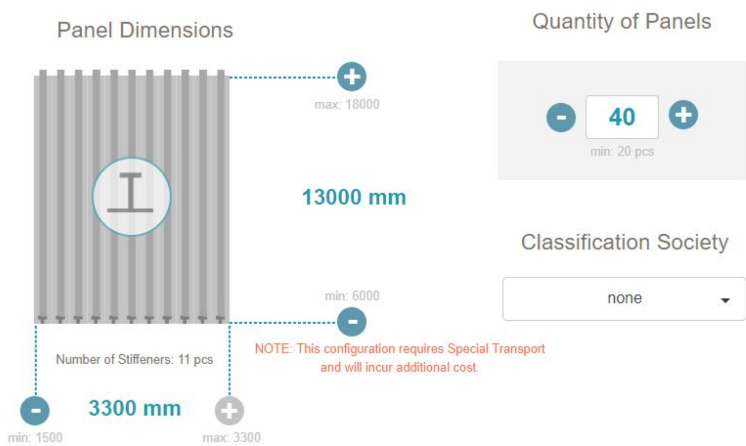
(a) Alloy and stiffener type.

(b) Size.



[51]

(c) Deck thickness and stiffener spacing.



(d) Panel dimensions and quantity.

[51]

Figure E.2: Procedure when ordering standard FSW T-profiles from Hydro.

E.3 Production Costs

Pricelist

Description	Panel no. and rev	Length (mm)	Width (mm)	Quantity (pcs/order)	Price (SEK/pcs)
Plank 350x50-3 mm	New 1	13 000	3 150	40	30 106
Floor 350x60P-4 mm	New 2	13 000	3 150	10	27 968

Remark 1: Prices are valid for one order and one delivery

Remark 2: Please note that panel width > 2401 mm requires an open truck, means no walls or roof. Risk for that panels become dirty during transport in bad weather conditions

Remark 3: New 1 = 9x Hydro no Plank 350x50-3mm
New 2 = 9 x Hydro no Floor 350x50-4 mm

Share of die cost

Description	Share of profile dies (SEK)
Plank 350x50-3mm	49 000:--
Floor 350x50-4 mm	49 000:--

Appendix F

Concepts

F.1 Concepts Presented to Marine Aluminium

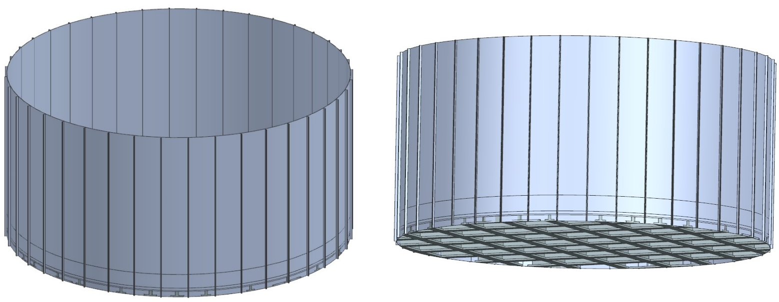


Figure F.1: Illustration of the concept with a flat bottom.

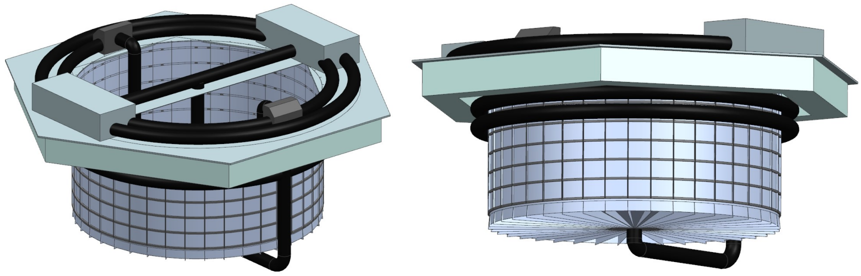


Figure F.2: Illustration of the concept with a panel based bottom.

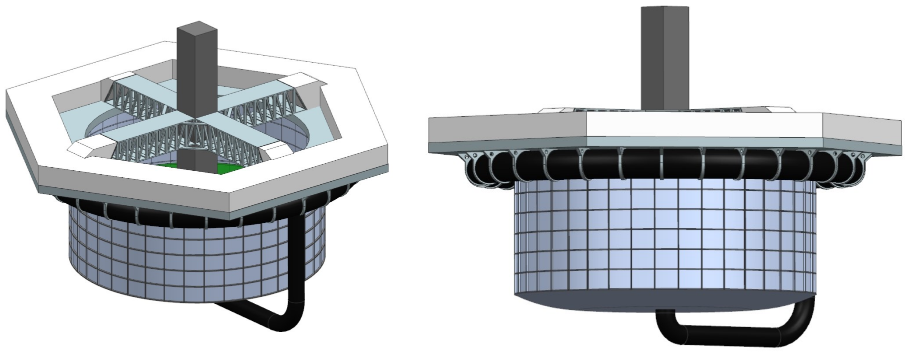


Figure F.3: Illustration of the concept with a single-part bottom.

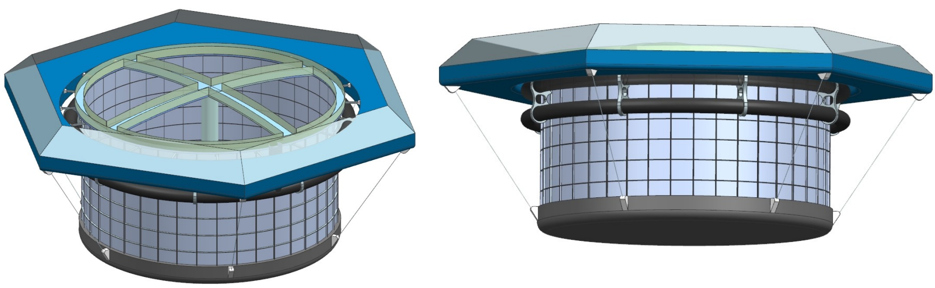


Figure F.4: Illustration of the concept with a concrete bottom.

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