Nora Skaret-Thoresen and Rakel Skaret-Thoresen

Development of a Modular Design Process for Customised Closed Containment Systems

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Supervisor: Bjørn Egil Asbjørnslett and Pål Lader
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NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

NTNU
Kunnskap for en bedre verden

Summary

Norway is presently the worlds biggest producer of Atlantic salmon. Still, further growth is expected as the government has stated a goal of multiplying the production volume by five within 2050, baseline being 2010. The industry is facing several challenges related to traditional technology, and there are concerns related to escapes, pollution, sea-lice and diseases. To circumvent these shortcomings closed containment systems is a viable solution as the farmer has increased control of the interaction between the farmed fish and the environment. However, compared to the number of market players supplying traditional fish farms, few manufacturers supply closed containment systems. This fact, combined with the short time period the product has been commercially utilized, leaves limited knowledge and experience regarding the design process for these solutions. The overall objective of this thesis is to develop inside knowledge for design of customized closed containment systems, based on standardised modules. This work requires a three-fold approach, including a technical aspect, a biological aspect and elements from system analysis and design.

The construction must be designed to be able to withstand the loads to which they are exposed at site, and at the same time facilitate good growth conditions. Through implementing a Preliminary Hazard Analysis, this paper maps hazardous events for closed containment systems along with related risk reducing measures. This knowledge contributes to increasing the understanding of how to design a safe system. In addition, functions that the systems must facilitate have been established. An important aspect of this work is to study the metocean effects from waves and current, acting on the construction. Based on the obtained knowledge, a simple tool that proposes an appropriate design for the customised closed containment systems is developed. The design is customised based on information from the production plan, site survey and additional customer wishes. This final design is assembled by 18 modules, of which eleven are standard in all deliveries and the remaining seven are customized for each delivery.

The modular product has the benefit of reduced design time and cost. Among other factors, this is because the design of standardised components only needs to be done once, and that certificates for main components like the floating collar are already available. The production efficiency is likely to increase, and the expected risk will decrease as it results in a higher chance of eliminating potential failures. The modularised closed containment system also facilitates exchange possibilities. It is decided to facilitate changes in design, for example if required by new laws and regulations like the revision of NS 9415:2009 will lead to. There are however some drawbacks of modularisation such as loss of flexibility, market orientation and increased structural volume and weight.

It is concluded that valuable inside knowledge for the design process is obtained. Based on evaluation of the advantages and drawbacks of the design, it is found that a modular design strategy is beneficial. Performing the case study has shown that the developed design tool is able to propose a customized design, based on information obtained from the customer. The level of detail of the proposed design is however low, and the grounds for decisions made related to the solution spaces are of varying strength. Improvements to the tool are therefore still required if it should be of any use.

Sammendrag

Norge er verdens største produsent av atlantisk laks. Videre vekst er i tillegg ventet da regjeringen har uttalt en visjon om å femdoble produksjonsvolumet innen 2050, sammenlignet med 2010. Vekst kan for øvrig ikke prioriteres for enhver pris, og blant forutsetningene for veksten er at dagens miljø- og sykdomsutfordringer løses og at en lykkes med innovasjon innen teknologi. Det sees mot lukkede anlegg som en potensiell løsning på flere av problemene som eksisterer for åpne, tradisjonelle oppdrettsanlegg. Spesielt når det kommer til de økologiske utfordringene, da oppdretter vil få økt kontroll over påvirkningen det indre miljøet har på omgivelsene når merden er lukket. Sammenliknet med antallet leverandører av tradisjonelle oppdrettsanlegg, er det få leverandører av lukkede sjøanlegg i Norge. Dette, samt den korte tidsperioden produktet har blitt benyttet kommersielt, er trolig årsaken til den begrensede kunnskapen og erfaringen som finnes for prosjektering av produktet. Det overordnede målet for denne oppgaven er å opparbeide bredere kunnskap om masseprodusert skreddersøm av lukkede anlegg, basert på et sett av standardiserte moduler. Oppgaven er forsøkt løst ved en tredelt tilnærming, der forståelse av teknologi, biologi og elementer fra systemanalyse og design står sentralt.

Gjennom utførelse av en grovanalyse er kritiske hendelser samt risikoreduserende tiltak for systemet forsøk kartlagt. Denne kunnskapen bidrar til å øke forståelsen av konstruksjonen og hvordan man gjennom designet kan redusere risikoen for uønskede hendelser. I tillegg ble en rekke funksjoner systemet må opprettholde utarbeidet. Dette innebar blant annet arbeid med å forstå de hydrodynamiske kreftene som virker på konstruksjonen.

Basert på den opparbeidede kunnskapen, er det utviklet et enkelt verktøy som kan foreslå et skreddersydd design av systemet, basert på standardiserte moduler. Produktet er skreddersydd etter informasjon om kundens produksjonsplan, informasjon fra lokalitetsanalysen og ytterligere kundevalg. Modulbaserte produkter assosieres gjerne med reduserte kostnader og tidsbruk i designfasen. Det lukkede anlegget vil også dra nytte av disse fordelene, da design og sertifisering av de standardiserte komponentene kun må gjøres en gang. Flytekragen er et eksempel på en slik modul. Videre er en fordel med det modulbaserte designet at effektiviteten i designfasen vil øke, og forventet risiko vil minke da sjansen for å oppdage feil er større for velutprøvde produkter. Designet tilrettelegger også for utskiftingsmuligheter på et senere stadium i produktets livsløp. Dette er gunstig, da arbeidet med å revidere NS 9415:2009 er i gang, og forandringer på eksisterende design kan bli nødvendig grunnet endringer i regelverket. Noen ulemper knyttet til det modulære design er redusert fleksibilitet, tap av markedsorientering og økt strukturelt volum og vekt.

Verdifull kunnskap om prosjektering av lukkede merder har blitt opparbeidet. Basert på designets styrker og svakheter, er det konkludert med at modulært design av dette systemet er gunstig. Case studiet viste at verktøyet fungerer som ønsket, i form av at det foreslår et skreddersydd design, basert på informasjon innhentet fra kunden. Detaljnivået av det enkle verktøyet er forøvrig lavt, og begrunnelsene for om en modul skal være standard eller skreddersydd er av varierende styrke. Forbedringer må derfor til om verktøyet skal ha noen kommersiell nytteverdi.

Preface

This paper is a master thesis written by two students enrolled at the Norwegian University of Science and Technology (NTNU), undertaking a masters degree in Marine Technology. The research was carried out in the spring of 2019, from January to June, and it is a continuation of the work on the project thesis from the autumn of 2018. The aim of this thesis is to develop inside knowledge for design of a customized closed containment system, based on standardised modules.

The authors would like to thank their two supervisors, Bjørn Egil Asbjørnslett and Pål Lader, from the Norwegian University of Science and Technology, who has been helpful providing guidance, support and feedback throughout the semester. They have always been willing to meet the authors for discussion, which has been very much appreciated. Further, the authors would like to express their gratitude towards Botngaard Systems for introducing the authors for this interesting topic. Einar Vik and the rest of the company's employees have shared their experience and knowledge, and also given advice and feedback throughout the process.

The Authors,
Nora Skaret-Thoresen & Rakel Skaret-Thoresen

Trondheim, June 11th 2019

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Dictionary

Abbreviations:

$ALARP$	=	As low as reasonably practicable
$CAPEX$	=	Capital expenditures
DSM	=	Design Structure Matrix
HOQ	=	House of Quality
PHA	=	Preliminary Hazard Analysis
PVC	=	Polyvinyl chloride
RAO	=	Response amplitude operator
RAS	=	Recirculating aquaculture system

Wave and water parameters:

H	=	Wave height
T	=	Wave period
λ	=	Wave length
k	=	Wave number
ω	=	Wave frequency
h	=	Water depth
ξ_a	=	Incident wave amplitude
ω_k, ω_j	=	Wave frequency of two different regular waves in sea stat
ξ_{aj}, ξ_{ak}	=	Incident wave amplitude of two different waves in sea state

Structural parameters:

D	=	Diameter of sh pen
A	=	Projected area
M	=	Structure mass
H_1, H_2	=	Height of top and bottom part of cage
T_{2n}	=	Natural period in sway

Forces and motions:

η_1	=	Motion in surge
η_2	=	Motion in sway
η_3	=	Motion in heave
η_4	=	Motion in roll
η_5	=	Motion in pitch
η_6	=	Motion in yaw
$\ddot{\eta}_2, \dot{\eta}_2, \eta_2$	=	Acceleration, velocity and motion in sway direction
ϕ	=	Velocity potential
ϕ_{01}	=	First order velocity potential of incident regular wave
ϕ_1	=	Total velocity potential
ϕ_D	=	Velocity potential Diffraction problem
A_{jk}	=	Added mass in j direction due to forced motion in k direction
B_{jk}	=	Damping coefcient in j direction due to forced motion i k direction
C_{jk}	=	Restoring coefcient in j direction due to forced motion i k direction
A_{22}	=	Added mass in sway due to sway motion
B_{22}	=	Damping in sway due to sway motion
C_{22}	=	Restoring in sway due to sway motion
k_{22}	=	Mooring line stiffness in sway direction
F_2	=	Force in sway
$F_{2excitation}$	=	Excitation force in sway direction
$F_{2radiation}$	=	Radiation force in sway direction
F_{2FK}	=	Froude Kriloff force in sway direction
F_{2diff}	=	Diffraction force in sway direction
F_{2df}	=	Difference frequency force aka. Slowly varying force in sway
F_{md}^{tot}	=	Total mean drift force in irregular sea state in sway
F_D	=	Drag force from current in sway direction
F_b	=	Buoyancy force
F_w	=	Weight
F_{D1}, F_{D2}	=	Drag force from current on top and bottom part of cage
P_{dyn}	=	Incident wave dynamic pressure

General physical denitions and parameters:

g	=	Gravity of Earth
p	=	Pressure
t	=	Time
n	=	Normal vector
n_2	=	Normal vector in sway direction
U	=	Current velocity
C_D	=	Drag coefficient
X, Y, Z	=	Inertial frame

Chapter 1

Introduction

This chapter introduces the background, the state of the art, the objectives and the structure of the thesis.

1.1 Background

The aquaculture industry is an important industry in Norway both when it comes to wealth creation and employee effect. In 2018 Norway exported 1.1 million tonnes of salmon worth NOK 67.8 billion, which is an increase of 5 per cent in both volume and value compared to 2017 (Norwegian seafood counsil, 2019). The Norwegian government has stated a goal of increasing the production volume from one million in 2010 to five million in 2050 (Norsk Industri, 2016). Growth can however not be prioritized at any cost, and due to challenges related to lice and the environment, the government has restricted further expansion of the industry (Olsen, 2018). To reach the goal of a fivefold increase by 2050, new solutions must be brought to light. Many of these challenges can be solved through the development of new technology. It is crucial that the technology development is carried out with an interdisciplinary approach, where an understanding of the environment and the fish's biological conditions are central (NTNU, 2019).

Closed constructions at sea is viewed as one possible solution to solving many of the problems faced by the fish farming industry today. The concept of closed containment systems has been tested out earlier but has not before recently proven to have commercial potential. The system can in short terms be explained as a floating structure with closed volume and controlled water exchange. The physical barrier is separating the farmed volume where the fish is staying, from the external environment. This way, it facilitates for control of both the sea lice and the impact on the surrounding environment. It is crucial that the fish farm is designed to be able to withstand the loads to which it will be exposed at a site. Hereunder loads from currents, waves and wind (Standard Norge, 2009). When it comes to design, the biological aspects are also an important consideration. To maintain good water condition and fish welfare is central to achieving good growth conditions, which again leads to higher profit for the farmer. To ensure that the abovementioned criteria are met a number of laws and regulations, encapsulating both the technical and biological aspects, must be taken into account during the design phase.

Redesigning a product for every new delivery is associated with increased design cost and time. The design method, modularisation, compromises between standardisation and customization, and it is well-tested on several marine systems. As of today, there does not exist a standardised modular design method for closed containment systems. This is presumably due to the limited time the closed technology has been utilized in the industry, in addition to that the product has yet to be supplied on a large scale. The demand for closed containment systems is however increasing, and there is reason to believe that developing a modular design of the system may be beneficial.

1.2 State of the Art

Research and knowledge of closed containment systems have increased drastically the recent years (Ctrlaqua, 2018). New technology has been developed, and challenges have been solved through an interdisciplinary approach, where an understanding of the biological aspects has been central (NTNU, 2019). Yet, a lot of research remains before the system is fully understood. An example is the response of flexible bags to external sea loads, a topic which is in need of further research (Strand, 2018).

As closed containment systems have been commercially utilized for only a short amount of time, the experience with the design of the product is limited. Most systems have until now been customised for each specific delivery, and experience from one delivery has been transferred to the next. As of today, no standardised modular design method for closed containment systems is available. Information on which parameters that must be considered when designing a closed containment system is also limited.

1.3 Objective of the Thesis

The overall objective of this thesis is to develop inside knowledge for design of a customized closed containment system, based on standardised modules. Customized in this case means to take environmental parameters and forces acting on that specific site into account in the design, adjust the design based on the production plan for that specific delivery, and to consider other customer wishes. Part of the design is with intention standardized to benefit from the advantages of mass production. This work requires a thorough understanding of the aquaculture system and the different components it consists of, in addition to information about the design process and the parameters affecting the design. The obtained knowledge shall be utilized to develop a simple design tool that can be used in an early stage of design. To achieve this, the following tasks should be covered:

A) Introduce design and modularization theory. The literature review will form the basis for strategies and analyses performed in order to designing the marine system.

B) Introduce the concept of closed containment systems. Designing a marine system requires understanding of the production strategy, the components the design consists of and insight into laws and regulations affecting the system. This will also be covered by the literature review.

C) Conduct a Preliminary Hazard Analysis to identify the hazardous events that may occur for a closed containment system in order to design a safe system. This is also done as part of the work of understanding the system.

D) Break the overall function of the system down into sub-functions with the intention of discovering beneficial design solutions. Describe the relevance of each function, introduce any physical effects they may include and discuss how the function can be fulfilled. An important part of this point is to provide a discussion on the methodology and theory necessary to carry out calculations of the hydrodynamic forces acting on a closed containment system.

E) Conduct a House of Quality analysis and construct a Design Structure Matrix as part of the process of establishing modules.

F) Develop a solution space for the characteristics within each module. Consider different options and debate why the resulting solution space was considered preferable. Hereunder information required for each specific delivery should be pointed out, and the impact this has on the final design should be accounted for.

G) Develop and present a simple tool that can be used to propose a customized design in an early phase.

H) Performe a case study in order to illustrate how to use the developed design tool.

1.4 Structure

Chapter 2 presents the methodology used in the study, along with a discussion on the sources of information.

Chapter 3 and 4 constitute the literature review. Design and modularisation theory, in addition to relevant modularisation analyzes, are presented in Chapter 3. Chapter 4 introduces the concept of closed containment systems.

Chapter 5 contains a Preliminary Hazard Analysis that is performed in order to obtain information used in the process of designing a safe system.

Chapter 6 presents the functions the closed containment system must facilitate.

Chapter 7 consists of a House of Quality and a Design Structure Matrix that are conducted in order to create modules. The final modules and their interfaces are presented.

Chapter 8 presents a simple tool that can be used to propose a customized design in an early phase.

Chapter 9 contains a case study that is performed in order to illustrate how to use the developed design tool.

Chapter 10 includes a discussion of the work.

Chapter 11 includes a conclusion and suggests further work of the paper.

Chapter 2

Methodology

In chapter 2 a flowchart of the chosen methodology is presented. It is explained how a threefolded approach is found beneficial to carry out the work and the sources to information are presented.

2.1 Presenting the Methodology

The overall objective is to develop inside knowledge for design of a customized closed containment systems, based on standardised modules. Well-documented design strategies are available for several marine systems, but not for closed containment systems. It is therefore found interesting to develop a standardised design method for this systems. This work covers several fields of studies, and require insight into relevant analyzes and theories. The combination of these methods forms the methodology.

Before describing the chosen methodology, a brief introduction to marine system design will be given. Figure 2.1 illustrates the system design of a closed containment system. The corners of the diamond represent the four design criteria; technical performance, risk, environment and economics. These should be considered in each of the design levels of the system which is the physical level, the digital level and the autonomous level. Marine system design consists of approaches, models and methods used to create marine systems of the future or to improve today's systems (NTNU, 2018).

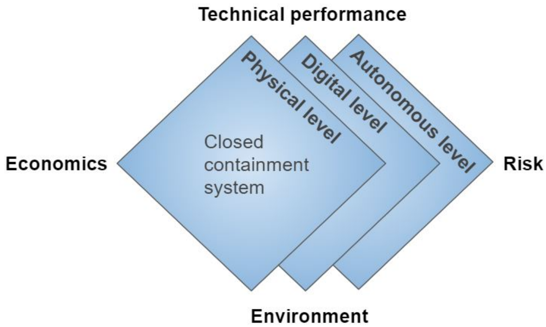


Figure 2.1: Marine system design applied on a closed containment system

Figure 2.2 shows a flowchart illustrating the methods that constitute the chosen methodology. Supplementary information or a brief explanation of the intended outcome of the methods is given in the figure.

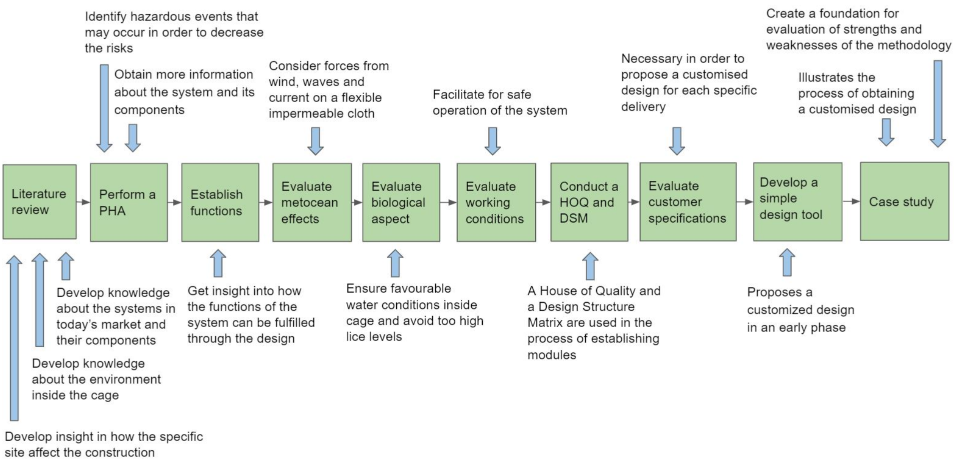


Figure 2.2: The methods that constitutes the methodology

The first step in the methodology is to conduct a literature review on both closed containment systems and relevant design theories. This step is mainly carried out to gain insight into the closed containment systems in today's market and the components they consist of. In addition, it provides knowledge on how the specific site affects the construction and how to maintain a beneficial environment inside the cage. A further understanding of the system is obtained by performing a Preliminary Hazard Analysis (PHA). The analysis is beneficial to conduct in an early stage of design as the system can be designed in a way that reduces the risk of hazardous events occurring. In the third step, the functions that the system will be designed to fulfil are established and described. This includes evaluations of metocean effects, the biological aspect and working conditions for the staff. Further, a House of Quality (HOQ) and a Design Structure Matrix (DSM) are used in the process of establishing modules. To propose a customised design for each specific delivery, relevant information from the customer is evaluated. This includes information about the customer's production plan, information from the site survey for the specific location and other customer wishes. The design method used in the simple design tool developed is modularisation, which balances the concepts of standardisation and customisation. The main essence of the modularisation concept is illustrated in Figure 2.3.

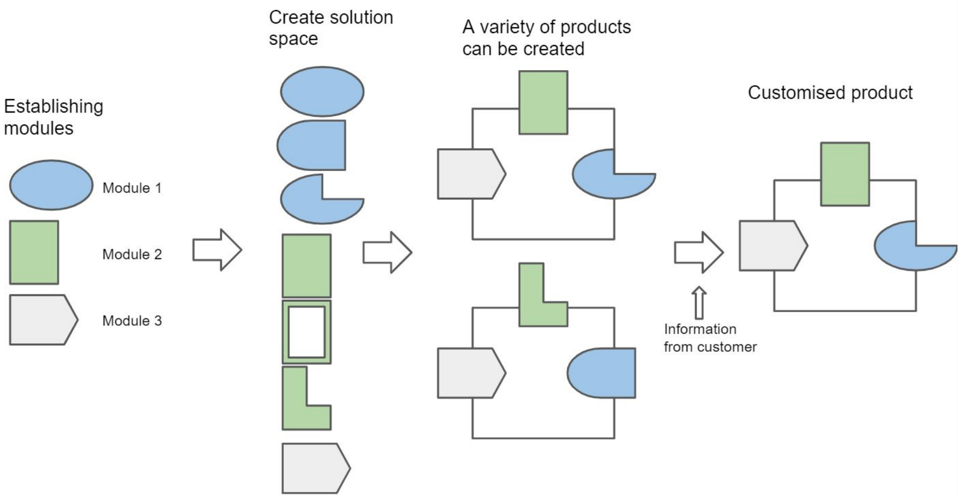


Figure 2.3: The steps of the modularisation concept

The figure above illustrates that the closed containment system is first divided into a given number of relatively self-sufficient modules. A beneficial solution space within each module is thereafter created. Some of the modules include multiple design alternatives, while others are standardised in all deliveries. Design of well functioning interfaces is crucial for the unit to work as planned, when all modules are being connected. A variety of customised products can be made from the different options in the solution spaces. Based on relevant information from the customer, a customized product is proposed to the customer.

The final step in the flowchart shown in Figure 2.2 is to perform a case study. This is done to illustrate the process of obtaining a customised design.

2.2 The Threefold Approach

In order to solve the overall objective, it was found necessary to encapsulate more than one field of knowledge. The threefold approach, illustrated in Figure 2.4, includes both a technological and biological aspect, in addition to elements from system analysis and design. The following paragraphs describes how the different fields are relevant.

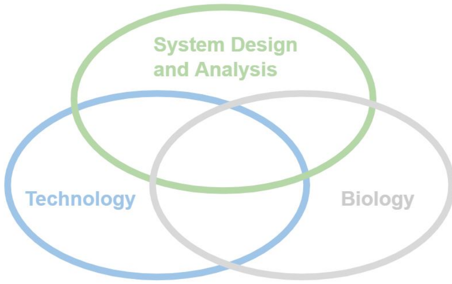


Figure 2.4: The threefold approach

Technology is a collection of techniques, skills, methods, and processes used in the production of goods, services or in the accomplishment of objectives (Wikipedia, 2019b). Technological insight is used as part of an engineering design process, in order to find solutions to problems or to improve existing solutions (Wikipedia, 2019a). In the design process of closed containment systems technology related to for example understanding of marine structures and hydrodynamics is of great relevance, as the construction is exposed to environmental forces from waves, wind and current.

The biological aspects do also have to be taken into account when designing the closed containment system. Fish welfare is required by law and it is essential to run a profitable business. For that reason, the design must facilitate for providing a favourable environment for the fish inside the cage. Along with insight into the biology of the salmon, biological understanding of the sea lice is also of interest, as sea lice poses a challenge in the industry (NTNU, 2018).

The goal of conducting a system analysis is to identify the objective of a system or part of a system. System design focuses on how to accomplish an objective. Further, the system analysis is a problem-solving technique that improves the system and ensures that all the components of the system work efficiently to accomplish their purpose. System design is a process of planning a new system or replacing an existing system by defining it's components or modules to satisfy the specific requirements (Tutorialspoint, 2019).

2.3 Sources to Information

In 2011, SINTEF stated that closed containment systems were still not commercialized, due to lack of research related to technology, biology and economy (SINTEF, 2011). Now, eight years later, the quantity of supplied closed containment system is still small, but increasing. This seems to be one of the reasons why the availability and accessibility of information sources related to this product have turned out being limited. For that reason, knowledge and experience provided by the employees of Botngaard System must be highlighted as an important source of information. There are reasons to say that the credibility of this information is relatively high, as Botngaard System have been developing their product since 2010 and is one of the leading suppliers of closed containment systems on the market. Through participation at *Brohodekonferansen 2018*, knowledge about some of the newest trends in the Norwegian fish farm industry was obtained. The speakers were some of the leading researchers within their field, and relevant information was gained during the two days long conference.

The design theory used in the thesis, is to a large extent inspired by the book *Engineering Design - A systematic approach* (Pahl et al., 2007). In addition, information on design theory was obtained through conversation with experts on the field. The two professors Stein Ove Erikstad from the Department of Marine Technology NTNU and Jan Ola Strandhagen from the Department of Mechanical and Industrial Engineering at NTNU have provided useful information on modularisation theory. Neither of them have experience with modularisation of aquaculture cages, but the consulting still provided valuable information transferable to design of the system.

During the process of understanding the environmental forces acting on the structure, theories from the basic marine disciplines, marine hydrodynamics and marine constructions were utilised. Analysing hydrodynamic forces that are acting on a flexible impermeable structure is challenging and the research on this field is still ongoing (Strand, 2018). Hence, several simplifications and assumptions were made when presenting the environmental forces acting on the closed containment system. Theories from the book *Sea loads on ship and offshore structures* was a well-used source (Faltinsen, 1990a).

Chapter 3

Design Theory

A design process can be carried out in a number of different ways, and in *Engineering Design* one possible approach is presented. The book describes the product development process which includes product planning, clarification of task and also a description of the conceptual and embodiment design phase. Further, it provides stimulation for the search for solutions and introduces an approach for developing size ranges and modular systems in order to reduce development effort. The methods described are mainly intended for the design and development of new products. However, they can also be helpful when existing products or components should be improved. In these cases, the methods have to be selected for, adapted to and used in accordance with the context of the problem. The book sets out a comprehensive design methodology for all phases of the design planning, design and development processes for technical systems, and is accordingly a contribution of information for this thesis (Pahl et al., 2007).

3.1 Establishing Functions to Facilitate a Beneficial Design Solution

The following section introduces how establishment of requirements and functions can be used to develop a beneficial design solution for a technical system. The information about an optimal solution is obtained from Chapter 3 in *Engineering Design* and the information about requirement lists and function establishment is from Chapter 6 (G. Pahl, 2007a) (G. Pahl, 2007b).

3.1.1 An Optimal Solution

The main task of engineers is to apply their engineering and scientific knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by technological, material, economic, legal, environmental and human-related considerations. A systematic approach is advantageous for this so that the designer does not have to come up with a good idea at the right moment. Solutions can be systematically elaborated using relevant methods. An optimal solution should:

- Fulfil all demands in a requirements list as well as most of the wishes.
- Fulfil all the functions established for the system.
- Be realised by the company within the constraints of budget, time-to-market, production facilities, etc.

Several steps are required to realize such a solution. Without going into detail, the first step towards achieving an optimal solution is to generate a range of possible solutions for the given task. The basis for this can be a function structure or another structure that is used to divide the overall task into manageable subtasks. In the second step, one or more possible physical effects are assigned to each of the sub-functions in order to realize the solutions. A solution space is obtained as alternative design solutions, fulfilling the functions the system must facilitate, is created. An optimal solution is described because it should be kept in mind that the overall goal of establish the functions of the system is to obtain an optimal solution.

3.1.2 Creating a Requirement List

To identify and document the requirements that determine the solution and embodiment of a product, the following questions should be answered:

- What are the objectives that the intended solution is expected to satisfy?
- What properties should it have?
- What properties should it not have?

The result of this process is a requirements list. The procedure for establishing a requirement list involves two stages. In the first stage, the obvious requirements are defined and recorded. In the second stage, these requirements are refined and extended using special methods. The requirements should be identified either as demands or wishes. Demands are requirements that must be met under all circumstances, and wishes are requirements that should be taken into consideration whenever possible. It could also be helpful to differentiate between implicit and explicit requirements, and according to, these specific types of requirements can be formulated:

- **Basic requirements:** These are always implicit requirements, and their fulfilment is self-evident and vital for the customer. Success or failure of a product is determined by these requirements.

- **Technical performance requirements:** These are explicit requirements and are articulated by the customer. They are usually specified precisely, for example, a new engine may have to have 15 kW of power and weigh not more than 40 kg. Such concrete values are used by customers when comparing competing products.
- **Attractiveness requirements:** These are also implicit requirements. Customers are usually not aware of these. However, they are used to differentiate between competing products.

3.1.3 Establishing Functions

As described above, the requirements facilitate for meeting the specifications of the final solution. It will now be described how establishing an overall function and corresponding sub-functions contribute to reaching this goal. The link between the requirement list and the functions is that the functions in some cases are established based on information from the requirement list.

The overall function of a system can be more or less complex, and therefore it can be helpful to break it down into sub-functions of lower complexity. One can structure the sub-functions of a system by establishing some kind of function structure. It facilitates the discovery of solutions because it simplifies the general search for them, and also because solutions to sub-functions can be elaborated separately. Individual sub-functions can be described by more concrete statements like physical effects, geometric characteristics and material characteristics.

When establishing a structure for the function of a system, it is often distinguished between original and adaptive designs. This is because the degree of detail used depends very much on the novelty of the task. In the case of original designs, the basis of a function structure is the requirements list and the abstract formulation of the problem. In the case of adaptive designs, the starting point is the function structure of the existing solution obtained by analysing its elements.

When establishing functions the following points should be kept in mind:

- Start with the main functions of the system and that break them down into related sub-functions.
- From a rough structure, or from a function structure obtained by the analysis of known systems, it is possible to derive further variants and hence to optimise the solution, by breaking down or combining individual sub-functions, changing the arrangement of individual sub-functions or by moving the system boundary.
- The function arrangement should be kept as simple as possible, in order to encourage simple and economical solutions. To this end, it is also advisable to aim at the combination of functions to obtain integrated function carriers.

3.2 Modularisation

This section will introduce the modularisation concept. Relevant definitions are presented, advantages and limitations of modular systems are discussed and different types of modularisation are introduced in addition to characteristics of the modules.

3.2.1 Definitions

The idea of modularisation is defined in many ways depending on the field of study. But, the main essence is that a system is divided into smaller parts or components, which must be relatively self-sufficient. By recombining these parts, according to a set of rules, multiple end products can be made. Thus, a broad variety of products can be produced by combining a limited number of modules. If it is done right, modularity balances standardisation and rationalisation with customisation and flexibility (Miller and Elgard, 1998).

According to Melissa Schilling, modularity is defined as a general system concept (Schilling, 2000). ”It is a continuum describing the degree to which a systems components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the ”rules” of the system architecture enable the mixing and matching of components”, she states. Professor Stein Ove Erikstad explains that ”to simply splitting a system into random parts, for later to assemble it, is not necessarily modularisation (Erikstad, 2009).” This means that there must be a certain level of flexibility in the way that the parts are recombined.

Modul
Over time, the definition of a module has changed from being defined by the physical presence of an entity or system, to being defined by its structure and functionality. When adding the functions for all modules in a system, it should fulfil the needed functions of the final product. Each module can be defined as a standardised system with given interfaces, which again makes it able to connect to the other modules in the platform (Miller and Elgard, 1998). An example of a function module is the power supply for the feed barge at a fish farm.

Modular product architecture
Modular product architecture is a form of product design that uses standardised interfaces between components to create a flexible product architecture (Sanchez and Mahoney, 1996). A strict set of rules must be followed when designing the interfaces between the modules. This is crucial for the unit to work as planned when all modules are being connected. One of the advantages of modular product architecture is that it makes it possible to design and develop modules independent of each other. This means that different companies can produce the module, but still be assured that they are contributing to producing a reliable, high quality, end-product. This promotes strategic flexibility, as each company has the possibility of quickly responding to changes in the market and technology (Baldwin and Clark, 2003). The opportunity of constantly developing and testing new ideas, and being able to improve the modules constantly, distinguish modular subcontractors from general subcontractors.

Product platform
A product platform is defined in several ways in the literature. One definition is "a structured, coherent collection of resources, including systems and template hierarchies, textual components, variants, rules and interface definitions, from which a range of customized product definitions can be derived" (Erikstad, 2009). The modules are individually independent of each other and can be replaced when desired. The platform, on the other hand, is a basic framework of the system and should be used over a longer period of time.

Modularity
Modularity is a system attribute, and it is related to construction and functionality. A modular structure is characterized by consisting of independence modules, connected by standardized interactions. By replacing one variant of a module with another, a new end-product is created. Thus, modularity is a dualistic concept which depends on both the module itself and the structure of the system it belongs to (Miller and Elgard, 1998).

Modularisation
Modularisation is described as the activity in which the structuring in modules takes place. It has the ability to balance two opposite forces; standardisation and customisation. Modularisation is defined by three main characteristics. The first one is connected to customisation. The company must be able to supply tailored products, but not at the expense of efficiency. This leads to the second driver behind modularisation, which is the utilisation of similarities. This includes reuse of resources and to use experience to standardise parts of the system. The third characteristic is to reduce complexity. This is a product of dividing the system into smaller independent systems, which also makes it possible to work on several less complex tasks at the same time (Miller and Elgard, 1998).

3.2.2 Advantages and Limitations of Modular Systems

Different stakeholders have different motivations for modularisation. In this section, the key drivers and drawbacks of modularisation will be discussed. The bullet points represent what Volker Bertram summarise as the most important elements of modular ship design, and the more detailed description that follows, is based on the book *Engineering Design* and the modularisation compendium written by Stein Ove Erikstad (Bertram, 2005) (Pahl et al., 2007) (Erikstad, 2009).

Key drivers for modular systems:

- Reduced design- and construction costs
- Reduced design- and construction time
- More flexible for later upgrades
- Shorter and cheaper maintenance periods

For modular systems, the design and construction costs are reduced, as ready documentation is available for tenders, project planning and design. The design is done once and for all, and additional design is needed for unforeseeable orders only. This will also reduce the design and construction time, and users can therefore expect a shorter delivery time.

The production efficiency is likely to increase, and the expected risk will decrease as it is a higher chance of eliminating failures.

Modularisation does also have the benefit of providing the opportunity of product variety and customisation, as it facilitates better exchange possibilities. Repair and maintenance can be conducted more efficient, which will save time and expenses. Better spare parts can be offered to the user, and the replacement costs will likely decrease as it is not necessary to replace the whole product, only the module or component with a failure or damage.

From an environmental point of view, modularisation can be beneficial. Components with approximately the same lifetime can be placed in the same module so that only parts of the product can be replaced instead of the whole product. This will again increase the products lifetime. In addition, components of the same material can beneficially be placed in the same module, as this is advantageous when it comes to recycling of the module or product.

Drawbacks of modularisation:

- More effort must be put down in the initial design phase
- Reduced design flexibility
- Usually higher weight
- Usually more space demanding

Drawbacks from modularisation are that more effort must be put down in the initial design phase, which is time- and cost demanding. Adaptation to special customer wishes are not as easily made as they are with individual design, so another downside of modularisation is therefore the loss of flexibility and market orientation. Since the interests of both the users and the producers have to be taken into consideration, the determination of an optimal modular system may prove very difficult as well. By desire of product changes, it can be considered at long intervals only because once-and-for-all development costs are high.

Weight and structural volumes of modular products are usually greater than those of specially designed products, and the technical features and overall shape are more influenced by the design of modules than they would be by individual designs.

3.2.3 Types of Modularisation

In literature, there is some disagreement on how many basic types of modularity that exist. The book *Product Design and Development* describes the three different types as follows (Ulrich, 2008):

- **Slot modularity:** The interface is specific to the module type, meaning that each of the interfaces between the components is of a different type from each other. This makes it impossible for the various components of the product to interact, and that there is only one possible way of connecting the modules with each other.

- **Bus modularity:** The interface is standardised across several module types. This means that physical components are connected to a common bus via the same type of interface.
- **Sectional modularity:** This sectional architecture does not involve a single module to which the components can attach. Rather, all modules have one or a few common interfaces, which allow them to connect to each other. This is characterized by chained interconnection of modules.

Figure 3.1 illustrates the difference between slot, bus and sectional modularity.

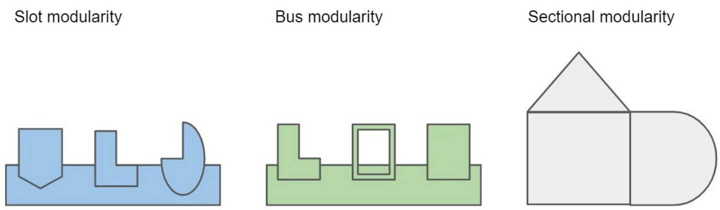


Figure 3.1: Different types of modularisation

3.2.4 Classification of Modules

Classification of modules are not clear-cut and can be done in several ways. One way is to distinguish between function and production modules. Production modules are designed independently of their function and are based on production considerations alone. Function modules help to implement technical functions independently or in combination with others. For the classification of function modules, it seems advantageous to define the various types of function that recur in modular systems and can be combined as sub-functions to fulfil different overall functions. It is further distinguished between essential and possible modules. Certain basic functions are fundamental to a system and are not variable in principle. A basic function can fulfil an overall function simply or in combination with other functions. This is implemented as an essential module which may come in one or several sizes, stages and finishes. Special functions are complementary and task-specific sub-functions that do not need to appear in all overall function variants. They are implemented in possible modules that are additional to the basic modules (Pahl et al., 2007).

3.2.5 Optimum Number of Modules

For the characterisation of modular systems, their resolution should be considered. That means the extent to which a particular module can be broken down into individual parts, for functional or production reasons. For the modular system as a whole, the resolution defines the number of individual units, and their possible combinations. The determination of the optimum number of modules is however a complex task. It is influenced by the following factors (Pahl et al., 2007):

- Requirements and quality must be maintained and the propagation of errors must be taken into account. Thus the greater the number of individual components, the greater the number of fits, and this may have untoward repercussions on the function.
- Overall function variants must be created by the simple assembly of modules.
- Modules may only be broken down to the extent that functions and quality permit and costs allow.
- In modular products marketed as overall systems, variants of which clients can assemble themselves by combinations of the modules, the most common modules must be designed for equal wear and tear and easy replacement.
- In determining the most efficient modularity with regard to costs and production times, designers must pay special heed to the costs, not only of the design itself but also of production, including production planning, production processes, assembly, handling and distribution.

3.2.6 Size Ranges

In many cases, the market is demanding various sizes of a product. Therefore modular products often involve size ranges. The aim of size ranges is the rationalisation of product development by the implementation of the same function with the same principle solution, and if possible, with the same properties over a wide range of sizes. Modular systems provide rationalisation in a different situation. If a product is to fulfil different functions, then many variants will have to be provided at great cost in design and production. Rationalisation is however possible if the particular function variant is based on a combination of fixed individual parts and function units, this is what a modular system sets out to achieve (Pahl et al., 2007). The most important key drivers and drawbacks associated with size ranges are listed below (Pahl et al., 2007).

Key drivers for size ranges:

- The design work can be done once and for all and can be used for a host of applications.
- The production of selected sizes can be repeated in batches and hence becomes more cost-effective.
- Higher quality is possible.
- Competitive and high-quality products.
- Short delivery times.
- Easy acquisition of replacement parts and fittings.

Drawback of size ranges:

- Limited choice of sizes, not always with optimum operational properties.

In general, when rationalising a product size range, the increments will be selected once and for all. An appropriate selection of step sizes, for instance with respect to available fish farming volume, is established. The selection can be based on several considerations. First of all on the market situation, which as a rule requires small increments so that the varied demands of customers can be met most effectively. The second consideration is efficient design and production. For technical and economic reasons, the selected step sizes must be fine enough to meet the technical demands, but yet coarse enough to allow large-batch production based on a simplified range (Pahl et al., 2007).

The selection of step sizes involves information about market expectations in respect of the individual sizes. As the optimum selection of step sizes must be based on several factors, it is not always possible to opt for a constant step factor, more often considerations will demand the break up of a particular range of sizes into several sets (Pahl et al., 2007).

3.3 House of Quality

Conducting a House of Quality analysis is found suitable as part of the process of establishing modules. Theory about this method will be provided in this section. The House of Quality analysis has received its name due to the roof-like structure in its top. This house is divided into rooms, and the structure of these matrices will be presented in the following. Figure 3.2 illustrates the different "rooms" of the House of Quality. The illustration is created in the diagram software Edraw Max.

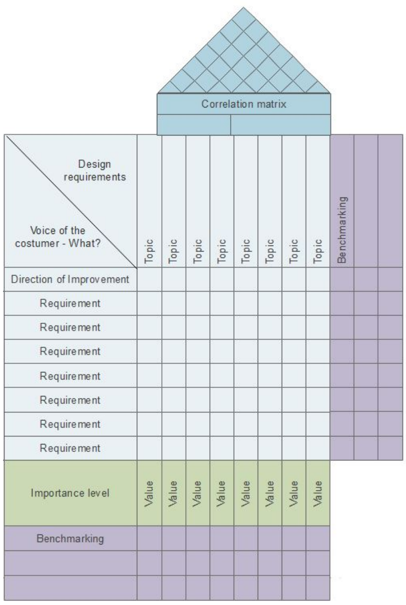


Figure 3.2: A House of Quality diagram, consisting of different "rooms"

Voice of the customer - What?

What do customers want? House of Quality begins with the customer and the establishment of objects, which represents the answer to ”What?”. Three kinds of service characteristics can be used to describe the client’s requirements (Bernal et al., 2009):

- **Performance requirements:** The requirements mentioned directly by the clients.
- **Basic requirements:** Essential parts of the service that perform basic functions that the user expects and considers as given.
- **Emotional requirements:** It reflects a need that the client has not appreciated before.

Different methods are used to map these requirements. Some Japanese companies simply place their products in public areas and encourage potential customers to examine them, while design team members listen and note what people say. Usually, however, more formal market research is called for, via focus groups, in-depth qualitative interviews, and other techniques (Hauser and Clausing, 1988).

Design requirements
How can we change the product? Next comes the definition of ”How”, which is the design requirements of the service. It defines how each client’s requirement will be satisfied by the service. These features are measurable and can be evaluated at the end of the development process (Bernal et al., 2009).

Relations matrix
The relations matrix represents the relation between the client’s requirements and the design requirements. The relationship is not always 1:1, they can be complex and varied in strength. Also, a single design requirement may influence several of the client’s requirements. Three strength levels are defined; weak relation, medium relation and strong relation. If the column is empty it indicates that there is no relationship between the client’s requirement and the design requirement (Bernal et al., 2009).

Benchmarking
The ”room” of Benchmarking allows for competitor assessment. The competitor’s services are compared to the company’s services and the benchmarking is carried out for ”What” and ”How”. The companies services are compared along the lines of both client requirements and for design requirement fulfilment. A characteristic measure is determined for each service feature (Bernal et al., 2009).

Importance level
The relative significance of each client’s ”What” and ”How” to achieve the desired goal, is stated in the importance level. The relative significance of the ”What”-s is established through an evaluation by the customer. In the relative scale, the customer’s importance is seen as more significant the larger the number is. For each number ”How”, the ”What” importance level is multiplied by the corresponding weighting, and this creates value for each relationship between client and design requirement. By adding the values together, the importance of the design requirements is revealed (Bernal et al., 2009).

Correlation matrix
Last but not least is the correlation matrix, represented by a triangular table. ”How” is integrated by establishing the correlation between all of the elements, and the matrix describes the strength of the relationship between the design requirements. The aim is to identify which requirements support each other and which do not (Bernal et al., 2009).

3.4 Design Structure Matrix

The design structure matrix is a representation and analysis tool for system modelling. By the use of a squared matrix, the relationship between elements in a system is displayed in a compact, visual and analytically advantageous format (Browning, 2001). The method is mainly used in the development of technical complex systems by listing the components in the system as system elements in the rows and columns. A Design Structure Matrix is well suited for establishing system modules, which is done by grouping elements that are connected (Technical University of Munich, 2018). It is distinguished between four types (Browning, 2001):

- **Component-based Design Structure Matrix:** Used for modelling system architectures based on components and/or subsystems and their relationships.
- **Team-based Design Structure Matrix:** Used for modelling organization structures based on people and/or groups and their interactions.
- **Activity-based Design Structure Matrix:** Used for modelling processes and activity networks based on activities and their information flow and other dependencies.
- **Parameter-based Design Structure Matrix:** Used for modelling low-level relationships between design decisions and parameters, systems of equations, subroutine parameter exchanges, etc.

As the system being evaluated in this report is a closed containment system, a component-based Design Structure Matrix is decided to be the relevant type. The method includes three main steps. First, decomposing the system into elements. Thereafter understanding and documenting the interaction between the elements. This is done numerically, by letting a number represent to what degree the components are dependent on each other (Browning, 2001). Finally, a clustering process is carried out to establish the modules. This is done by finding subsets of components that do interconnect with each other, but not so much with the rest of the system (Technical University of Munich, 2018).

Chapter 4

Introducing the Concept of Closed Containment Systems

This chapter introduces the concept of closed containment systems and its position in today's market. In section 4.1 the different types of cage concepts are categorised. The traditional production cycle of Atlantic salmon is described in Section 4.2. This is done in order to discuss the alternative production strategies that are suitable for closed containment systems. Further, the closed concepts in today's market are presented in Section 4.3. Section 4.4 includes an overview of the main components of closed containment systems and presents a list of components that will be used in the process of establishing modules. In the last section, the most relevant laws and regulations related to the design process of a closed containment system will be introduced.

4.1 Categorisation of Fish Farming Concepts

There are several types of cages in today's market. The different concepts vary when it comes to design and function, and will now be categorised. Today the majority of farmed fish in Norway is produced at sea in so-called traditional fish farms. These cages are designed based on technology developed in Norway in the 70's. Net-based fish farming systems facilitates the simplest form of operation, as the water replacement in the system happens naturally due to the current in the ocean. Closed containment systems are traditionally not so much used. This is mainly because traditional fish farms have been superior when it comes to ease of establishment, operation and profitability (Rosten et al., 2018). Fish farms floating in the sea can be divided into two main categories:

- Open net pens, often referred to as traditional fish farm
- Closed, floating constructions

An open cage for fish farming at sea, consists of a net-shaped bag, where a net-wall represents the barrier between the farming volume inside the bag and the external environment. It is no management of water replacement inside the net pen and no defined water outlets. A closed cage is a floating structure with closed volume and controlled water exchange. A physical barrier is separating the farming volume where the fish is staying, and the external environment. Biologists and engineers will often see the term ”closed” in different ways. When analysing from an engineer’s point of view, partly permeable constructions are also viewed as closed. Therefore a cage with for example a cloth as the barrier, is referred to as closed.

Constructions at sea are often referred to as ”closed, floating constructions” as this is the most known form. However, it also includes constructions that are permanently standing on rigid ground or constructions that are submerged. Furthermore, the closed floating containment systems are divided in three categories (Snøfugl, 2015):

- Closed, flexible structure
- Closed, semi rigid structure
- Closed, rigid structure

Closed, flexible structures can be made of different types of fabrics or fibre reinforced cloths, closed, semi rigid structures can for example be made of glass fibre reinforced plastics and closed, rigid structures can be made of different rigid materials like plastic, concrete or steel.

From now on it will be focused on closed flexible structures, referred to as closed containment systems, as that is the type of cage the design process in this thesis will consider.

4.2 Production Strategies

A typical production cycle for farmed Atlantic salmon will be described in this section. Closed containment systems are not necessarily intended to replace traditional fish farms for the whole production phase. Three typical productions strategies including closed containment systems will further be presented.

Traditional production cycle of Atlantic salmon

The Atlantic salmon production cycle lasts for about 3 years. During the first 10-16 months of production, it goes from egg to alevins, fry, par and ends up as a smolt. First, the eggs are fertilised and then the fish is grown to approximately 100-150 grams in a controlled freshwater environment. Landbased production facilities using RAS technology or flow through is mainly use for this (Marine Harvest, 2018). During the production cycle, the fish goes through physical changes. This includes the transformation to smolt which is called smoltification and is when the fish adapts to seawater, changes colour and shape of its body (Heggberget et al., 1992). After the smoltification, the fish is transported to traditional fish farms in the sea for a period of 12-24 months. It stays there until it has grown to a market size of 4-5 kg. When the fish reaches harvesting size, the fish is transported to processing plants where it is slaughtered and gutted (Marine Harvest, 2018).

Production strategies including closed containment systems

Figure 4.1 illustrates a traditional production strategy and three prominent production strategies that includes closed containment systems (Ctrlaqua, 2018).

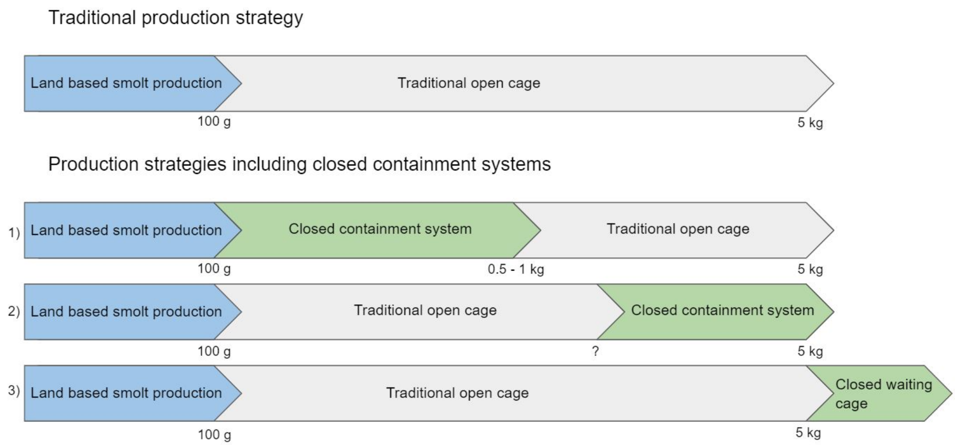


Figure 4.1: Production strategies of Atlantic salmon

The production strategies are either for production of post-smolt, use for on-growth or as waiting cages (Botngaard, 2018c). The first of these strategies is based on moving the post-smolt, of approximately 100 grams, to a closed containment system instead of directly to an open net pen. The concept is based on the assumption that if the post-smolt grows to about 0.5-1.5 kg in the closed containment system, it is protected from the environment in its most vulnerable phase. Strong and robust, it is transferred to open cages. This strategy is supposed to result in a higher growth rate, lower mortality and no lice problems. This shall lead to reduced production time and economic benefits (Ecomerden, 2018a). The design process in this thesis will be based on this production strategy.

The second strategy involves moving the fish to a closed containment system for the final on-growing. This can both be used when the fish is at risk due to high lice pressure or to protect broodstock during the last months in the sea. This is strategic as the economic loss per fish is peaking as it approaches harvest weight (Botngaard, 2018a).

The third strategy includes transferring the salmon that is ready for slaughtering to a closed waiting cage. This is an alternative to sanitation slaughter from well boat (Botngaard, 2018a).

4.3 Closed Containment Systems on Today's Market

Early 2019, when the literature review was conducted, it was found 15 suppliers of closed containment systems in Norway. They are listed in Table 4.1, and the information about the different concepts are obtained from their respective websites.

Table 4.1: Closed containment systems on today's market

Category	Name	Company
Do not rely on development licenses		
Closed flexible structure	Botngaard System	Botngaard System AS
Closed flexible structure	Ecomerden	Ecomerden AS
Closed flexible structure	Greenbag	Merdslippen AS
Closed semi rigid structure	Neptune	Aquafarm Equipment AS
Closed semi rigid structure	AquaDome	MSC aqua AS
Closed rigid structure	Agrimarine System	AgriMarine
Closed rigid structure	Salmon home nr 1	Fishfarming Innovation
Rely on development licenses		
Closed flexible structure	AkvaDesign System	AkvaDesign AS
Closed rigid structure	Egget	Marine Harvest ASA
Closed rigid structure	AquaTraz	Midt-Norsk Havbruk Produksjon AS
Closed rigid structure	Marine Donut	PD Group AS
Closed rigid structure	Pipefarm	Stadion Laks
Closed rigid structure	Produksjonstank	Hydra Salmon Company AS

A list of the closed containment systems on today's market was desirable to make in order to get an overview of some of the existing concepts. The concepts of the highest interest are the once categorised as closed flexible structures. This includes structures supplied by the companies Botngaard System, Ecomerden, Merdslippen and AkvaDesign. All these designs are made for production of post-smolt. These concepts will be used as a base for mapping the typical components of a closed containment system.

4.4 Components

In this section, the main components of a closed containment system will be presented and listed. This list will later be used to create modules. Figure 4.2 illustrates an example of a closed containment system design.

Figure 4.2: Illustration of a closed containment system (Botngaard, 2018b).

4.4.1 Main Components

Net and cloth
The main function of the cloth is to serve as a barrier between the farmed fish and the surrounding environment. The impermeable cloth facilitates increased control of the interaction between the farmed fish and the environment, compared to traditional cages. The advantage of a double wall is to increases safety when it comes to escape of fish. In addition, the net is used when crowding the fish.

Mooring system
The function of the mooring system is to keep the fish farm in the correct position and to sustain the necessary volume of the cage. Transferring excessive forces to the other structural components of the cage should be avoided. Mooring systems are site-specific, as they must withstand forces generated by the environment. It must be powerful enough to resist the worst combination of static and dynamic forces expected at the site, under the worst weather conditions (Kumar and Karnatak, 2014).

Floating collar
The main functions of the floating collar is to provide the necessary buoyancy and maintain the volume of the net. It should be designed in a way that makes it easy and safe to walk on, as well as doing inspections and other work. Service vessels must have easy access for docking. It is crucial that the floating collar can handle forces from rough sea and wind, therefore it must be designed concerning challenges as corrosion, breaking and fatigue (Kumar and Karnatak, 2014).

Seawater inlet system
One of the great advantages of closed containment systems is the possibility of controlling the water that is pumped into the cage. If desired, both inlet and outlet water can be filtrated and UV treated to reduce the amount of pathogens and the chance of fish diseases. This

will further reduce the amount of infectious matter in the water that is pumped out of the cage (Rosten et al., 2018).

Control system
Based on feeding and environmental data from the cameras and sensors, the control system can provide production control, extensive and detailed traceability possibilities, and a platform for extraction of knowledge. A number of different software are available on the market (Steinsvik, 2019).

Oxygen supply
Having a sufficient amount of dissolved oxygen in the water inside the cage is crucial for production efficiency. This is due to the fact that oxygen is the main limiting factor of fish metabolism and essential in the process of food conversion. As closed containment systems are closed, they are well suited for maintaining an optimal level of dissolved oxygen inside the cage. The oxygen source could as an example be a liquid oxygen tank, an oxygen generator or an oxygen cylinder rack at the surface (Vard, 2018).

Sensors
Sensors are used to monitor both the fish and the feeding process. Environmental data such as temperature, oxygen, pH, salinity and current speed and direction, is important for making the correct farming decisions. The data can be viewed real-time or logged for later analyzes (AKVA group, 2019d).

Power supply
A well-functioning power system is crucial for a closed containment system as it is dependent on continuous water and oxygen supply. Emergency solutions as a back-up generator must also be installed in case of power shortage (Johnsen, 2012).

4.4.2 Component List

The components listed bellow will be used in the process of establishing modules. As mentioned in Section 4.3, there are several companies supplying flexible closed containment systems. The component list is based on these constructions, but mainly on Botngaard System's design.

- Floating collar
- Walkway
- Handrail
- Bird net
- Cloth
- Splash guard
- Net
- Mooring plate
- Mooring buoys
- Mooring thimbles
- Bottom attachment
- Mooring line
- Marker lights
- Seawater inlet pump
- Seawater inlet grid
- Seawater inlet pipe
- Riser
- UV treatment
- Elfilter
- Filter
- Waste pump
- Waste hose
- Waste collector
- Waste pipe

- Water outlet system
- Oxygen supply
- Oxygen source
- Sensors
- Cameras
- Control system with alarming
- Power supply
- Standby generator
- Feeding system
- Lights
- Dead fish handling
- Pullert
- Fender
- Rescue ladder
- Lifebuoy

4.4.3 Level of Detail

The level of detail in the component list was considered carefully. Both a too high and too low level of detail would be disadvantageous for the later work. This will be illustrated by using the component ”feeding system” as an example.

To divide the feeding system into smaller components like feed blower, feed doser, selector valve and air cooler was viewed as unbeneficial. This is because a too high level of detail would have resulted in an extremely high total number of components. As the components shall be used as input in several analyzes, it would be time-consuming to conduct the analyzes if the component list was too long. It would also be inexpedient as the components would, in any case, end up in the same module, because they constitute the same component. Doing this would therefore neither increase the quality of the final result.

4.5 Laws and Regulations

The national regulation for certification and inspection of fish farm systems given by the Norwegian government is called NYTEK. The regulation applies for all shareholders that farm fish in floating aquaculture installations in the Norwegian waters. The main purpose of NYTEK is to prevent fish from escaping through ensuring an adequate technical standard of all facilities. It points to technical standards, such as NS 9415, for specific technical requirements. NS 9415 is the most used standard, but equivalent standards with the same or higher safety level can also be used. NS 9415 consists of requirements for the site survey, risk analysis, design, dimensioning, production, installation and operation of a fish farm (Standard Norge, 2009).

The regulation requires that farmers can only use new plants and main components that are certified according to NS 9415 and that the certification must be done by an accredited certifications bodies. All main components except the mooring system must be product certified. This includes the floating collar, the net and the feeding barge. The mooring system must be designed by a company or a person that is certified, and a customized design must be made for each delivery (Fiskeri- og kystdepartementet, 2005). For existing plants, an accredited inspection body must approve that the facility meets the operational requirements of NS 9415. The Norwegian Accreditation is the Norwegian body for accreditation of certification bodies. Aquastructures, AkvaSafe and Åkerblå are examples of companies that are accredited (Norwegian accreditation, 2018).

Along with new technology and new fish farming concepts, a need for adjustments in the regulations arises. Therefore, a revision of NYTEK is in progress. Fish farming companies, suppliers of goods and services, in addition to interest organizations are some of the players contributing to the changes (Fiskeridirektoratet, 2018). Among others, the new regulation intends to be more appropriate for closed containment systems.

Chapter 5

Identification of Hazardous Events in order to Design a Safe System

In this chapter, a Preliminary Hazard Analysis is conducted for the main components of a closed containment system. The purpose of conducting it is to design a safer system and to obtain a better understanding of the system and its components.

5.1 Conducting a Preliminary Hazard Analysis

A Preliminary Hazard Analysis is a risk assessment method used to identify hazards and hazardous events mainly during the early design phase of a product. It identifies the critical components and the potential hazardous events that might occur, in addition to the causes, the frequency, the consequence, relevant safeguards and the risk of each hazardous event. The analysis helps to ensure that the system is safe. It is beneficial to carry out the Preliminary Hazard Analysis early in the design process as modifications are less expensive and easier to implement at this point. One of the main challenges considering the Preliminary Hazard Analysis is that the hazards must be foreseen (Utne, 2017).

The main steps of the Preliminary Hazard Analysis are listed below:

1. Identify hazardous event
2. Determine the frequency of the hazardous events
3. Determine the consequences of the hazardous events
4. Determine feasible risk reducing measures
5. Assess risk

The first step of the Preliminary Hazard Analysis is to identify hazardous events. Analysing every possible hazardous event would be too time and resource demanding, and therefore only the most critical events will be considered. In the process of identifying hazardous events, it is beneficial to collect information from someone with experience in the field. As Botngaard System has delivered several closed containment systems, the hazardous events in the Preliminary Hazard Analysis are strongly based on their experience. The hazardous events are categorised based on the main component they are connected to.

The second step is to determine the frequency of the hazardous events. Based on information obtained from Botngaard System, each hazardous event is assigned a frequency, ranging from 1 to 3. 1 indicates that the event occurs extremely infrequently, while 3 indicates that the event is expected to occur frequently.

The third step is to determine the consequences of the hazardous events. One event can lead to several consequences, but only the most critical consequence will be evaluated. It is differentiated between consequences for three different assets; people, environment and equipment. Each of these is divided into three categories, as shown in Table 5.1.

Table 5.1: Different categories for consequences in respect to different assets

Category	People	Environment	Property
3	Major injury or death	Escape of fish, dead fish	Huge technical error
2	Minior injury	Strongly reduced fish welfare	Significant technical error
1	No injury	Reduced fish welfare	Small technical error

The fourth step is to determine feasible risk reducing measures. Also here information from Botngaard System is utilized. The risk reducing measures can both refer to existing measures or measures that can be introduced or improved in order to reduce the risk.

The final step is to assess the risk. All hazardous events are ranked according to their risk priority number. This number is calculated by multiplying the category number of the consequence with the frequency. Figure 5.1 illustrates the risk matrix. Depending on the risk priority number, each hazardous event is grouped into a risk class with a corresponding colour. Green cells contain hazardous events with acceptable risk, yellow cells contain hazardous events with ALARP risk, and red cells contain hazardous events with unacceptable risk. ALARP means ”as low as reasonably practicable”, and the principle is that these risks should be reduced as far as reasonably practicable (Utne, 2017).

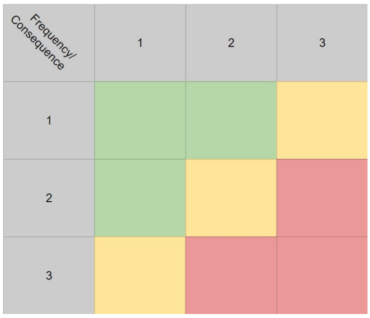


Figure 5.1: Risk matrix

The Preliminary Hazard Analysis for each of the main components are presented below, followed by a discussion of the results. The Preliminary Hazard Analyzes are made in Microsoft Office Excel.

Net and cloth

The Preliminary Hazard Analysis for the hazardous events connected to the main components net and cloth is shown in Figure 5.2. Eight hazardous events are presented, and four of these lead to a risk priority number of 3. The common characteristic for three out of four of these is that they concern a hole in the net. The following consequence of all four is therefore fish escape, which is an environmental consequence of category 3. The risk reducing measure is a double wall.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
1.a	Net/cloth	Hole in net in water outlet tube	Escape of fish	3	1	3	Net inside of the cloth
1.b		Hole in net in water outlet tube, may lead to wild fish entering the cage	Fish welfare	1	1	1	Net inside of the cloth
1.c		Damage due to bad weather, animals, vessels or other external forces	Escape of fish	3	1	3	Net inside of the cloth
1.d		Cloth attachment detached or destroyed	Escape of fish	3	1	3	Method tested and calculated
1.e		Lift, transport of equipment over the cage, use of feeder, damage of net/cloth during cleaning	Escape of fish	3	1	3	Net inside of the clothing
1.f		Sea water out. Outlet hatches plugged or overfouled	Fish welfare	1	2	2	Open hatches/remove fouling
1.g		Sea water out. To wide hatch opening or damage on clothing	Fish welfare	1	2	2	Adjust opening, check for damages on the cloth
1.h		Mass mortality, high amount of biomass ending up in the bottom of the net	Fish welfare	2	1	2	System for handling dead fish is considered. Solutions considered by farmer

Figure 5.2: Preliminary Hazard Analysis for net and cloth

Mooring system

Figure 5.3 shows the Preliminary Hazard Analysis for the main component mooring system. Two hazardous events are analysed. The most critical consequence is escape of fish, which is an environmental consequence of category 3. As the frequency category is 1, both the hazardous events are assigned a risk priority number of 3. From the risk matrix shown in Figure 5.1, it is defined that these events are having ALARP risks. Risk reducing measures are purposed in the Preliminary Hazard Analysis.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
2.a	Mooring system	Displacement of cage	Escape of fish	3	1	3	Mooring system approved by certification company
2.b		Damage on morring system due to external force, for example a vessel	Escape of fish	3	1	3	Procedure for traffic

Figure 5.3: Preliminary Hazard Analysis for the mooring system

Floating collar

Figure 5.4 shows the Preliminary Hazard Analysis for the floating collar. Five hazardous events are analysed, all having a risk priority number of 3, which means that this is an events with ALARP risks. In order to reduce the risk for event number 3.c, it is proposed that a overflowing water protector could be mounted on the floating collar. This is an example of a situation where it could be beneficial to facilitate later upgrades. Two of the hazardous events have the consequence injury or death. The staff's safety must therefore be kept in mind when making design decisions to the floating collar.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
3.a	Floating collar	Vessel or other external force makes hole in the ffloating collar, which leads to heeling	Escape of fish	3	1	3	The construction is divided into several bulckheads
3.b		Corrosion or fatigue, leading to beaking or leakage	Escape of fish	3	1	3	The construction externally approved, divided into several bulckheads and cathodically protected
3.c		Overfilling because of differences in salinity, errors in the pumps/instruments or water flowing over the floating collar in bad weather	Escape of fish	3	1	3	Independent sensors. Arrangement for evacuation of overflowing water. Possibility of adding a overflowing water protector
3.d		Staff falling into sea	Injury or death	3	1	3	Railings all along the floating collar and available lifebuoys. Use of lifejackets. Never operate alone
3.e		General risk of squeezing, falling etc.	Injury or death	3	1	3	All components must be designed to minimize this risk

Figure 5.4: Preliminary Hazard Analysis for the floating collar

Seawater inlet system

The Preliminary Hazard Analysis for the hazardous events connected to the seawater inlet system is shown in Figure 5.5. All hazardous events listed are in connection with the pumps. The two hazardous events concerning escape of fish, is assigned a consequence of 3, and end up with a risk priority number of 3. Also in this case, risk reducing measures are implemented.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
4.a	Pumps	Escape through pump at startup of pump	Escape of fish	3	1	3	Blockage at outlets
4.b		Daily operation. Bad quality of water due to high CO2 values and high total gas pressure	Fish welfare	2	1	2	Control of pumps. CO2 is logged continuously. If CO2 values are too high over a given periode of time, an alarm goes off. The outlet hatches are opened wide until the level is within the desired limit again
4.c		Power shortage or blockage of pump	Fish welfare	1	2	2	Converter restarts on a regular basis
4.d		Pump stops or hose plugged/collapsed	Fish welfare	1	2	2	Check the status of pump/hose
4.e		Pump runs on too low speed	Fish welfare	1	2	2	Turn the speed of the pumps up
4.f		Pump runs on too high speed	Fish welfare	1	2	2	Turn the speed of the pumps down

Figure 5.5: Preliminary Hazard Analysis for the seawater inlet system

Control system

The Preliminary Hazard Analysis for the hazardous events connected to the component control system is shown in Figure 5.6. The only hazardous event assigned a risk priority number of 3 is a power shortage. The consequence of this is fish dead, which can lead to huge economic losses for the farmer. Hence, a reliable risk reducing measure is very important. For the other hazardous events, the consequences are not that critical. These are mainly small technical errors, but due to a relatively high frequency, the risk priority number end up being 2. A reliable control system is therefore essential, in addition to effective risk reducing measures.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
8.a	Control system	Power shortage	Dead fish	3	1	3	Spare generator, extra oxygenation and removal of cloth
8.b		Daily operation. Bad quality of water due to high CO2 values and high total gas pressure	Fish welfare	2	1	2	Control of pumps. CO2 is logged continuously. If CO2 values are too high over a given periode of time, an alarm goes off. The outlet hatches are opened wide until the level is within the desired limit again
8.c		Power shortage or blockage of pump	Fish welfare	1	2	2	Converter restarts on a regular basis
8.d		PC-panel. Contact error or breakdown	Technical	1	2	2	Check the electricity supply, functionality, restart panel
8.e		Loss of signal from camera. Could be due to contact error or breakdown	Technical	1	2	2	Check cables and the electrical outlet
8.f		PC control room. Lost access from web-interface to PC-panel	Technical	1	2	2	Check the electricity, functionality or restart panel
8.g		Web connection. Network error or cabel/contact error	Technical	1	2	2	Consider the need of alarming by phone if ordinar interface is disconnected

Figure 5.6: Preliminary Hazard Analysis for the control system

Oxygen supply

Three hazardous events are analysed in the Preliminary Hazard Analysis for the oxygen supply. These are shown in Figure 5.7. For the event of no oxygen supply over a longer period of time, the most severe environment consequence, dead fish, will occur. Both backup systems and alarms are introduced as risk reducing measures. A reliable oxygen supply does hence shows to be essential in order to design a system which maintains the fish welfare.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
5.a	Oxygen supply	No oxygen supply due to power shortage	Dead fish	3	1	3	Alarm on phone. Back up generator. Extra oxygen supply by a diffuser hose
5.b		No oxygen due to errors in the O2 system	Dead fish	3	1	3	Alarm on phone. Back up generator. Extra oxygen supply by a diffuser hose
5.c		Reduced oxygen supply	Fish welfare	2	1	2	The amount of dissolved oxygen is monitored

Figure 5.7: Preliminary Hazard Analysis for the oxygen system

Sensors

The Preliminary Hazard Analysis for the hazardous events connected to the sensors is shown in Figure 5.8. Insufficient supply of oxygen is connected to the hazardous events that are assigned the highest risk priority number. An oxygen measuring device of good quality is crucial in these cases. Most of the other hazardous events in conjunction with the sensor system occur more frequently, but with a less severe outcome, resulting in a lower risk priority number. Alarming is used as risk reducing measure for several of the events.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
6.a	Sensory system	Oxygen. Generator do not start	Fish welfare	3	1	3	Oxygen bottle banks starts to deliver O2 instead. Alarm from O2 generator to control system
6.b		Oxygen bottle bank empty	Fish welfare	3	1	3	Pressur sensor on oxygen bottle bank that warns if the pressure is low. Pressure measuring device inside O2-regulation cabinet after valves. Gived an alarm signal if the pressure is bellow a certain level.
6.c		Oxygen. Pipe/hose fractured	Fish welfare	3	1	3	Pressur measuring device inside O2-cabin enables detection of hose fraction downstream of cabinet
6.d		Oxygen. O2 value too low. One or both of the O2-sensors measure low O2-values	Fish welfare	1	2	2	Increase the amount of O2 in the cage
6.e		Okxygen. O2 values are too high. One or both O2-sensors measure to high O2-values	Technical error	1	2	2	Reduce the amount of O2 in the cage
6.f		Level sensor. Too much water in cage, leading to it laying too low in the water	Technical error	1	2	2	Pumps provide less water
6.g		Level sensor. Icing	Technical error	1	2	2	Removal of ice
6.h		Level sensor. Plugged outlet	Fish welfare	1	2	2	Cleaning of outlet
6.i		Level sensor. Fouling on net/clothing, water outlet tube	Fish welfare	1	2	2	Removal of fouling
6.j		Level sensor. Insufficient amount of water in cage, leading to it laying to high in the water	Fish welfare	1	2	2	Pumps provide more water
6.k		Level sensor. Damaged clothing/too large opening in outlet	Fish welfare	1	2	2	Check the clothing for damages
6.l		Level sensor. The pumps have worked on maximal capacity too long, and the level sensor alarm has not gone off	Fish welfare	3	1	3	Warn about the issue
6.m		Too high deviation in salinity inside vs outside the cage	Escape of fish	3	1	3	Warn about the issue
6.n		pH. High CO2 level	Fish welfare	1	2	2	Control system allow for more water in the cage to remove some CO2. Warning level of level sensor must not be exceeded.
6.o		Temperature	Fish welfare	1	2	2	Logging of temperature
6.p		Turbidity. High level of particles in the water. Unable to remove sufficient amount of sludge	Fish welfare	1	2	2	Increase effect of sludge pump for a given periode. Warn of the high level
6.q		Level sensor, salinity, pH, temperature or turbidity. Error in contact, cable or sensor	Technical error	1	2	2	Warn of sensor error

Figure 5.8: Preliminary Hazard Analysis for the sensor system

Power supply

Two hazardous events are analysed in the Preliminary Hazard Analysis for the power supply system. These are shown in Figure 5.9.

Number	Component	Hazardous event	Consequence	Consequence (1-3)	Frequency	Risk priority number (RPN)	Risk reducing measure
7.a	Power supply	Back up generator do not start when it is needed	Dead fish	3	1	3	Periodic maintenance
7.b		Power shortage. No oxygen supply, pumps does not work, sensory system does not work	Dead fish	3	1	3	Back up generator. Cut the cloth

Figure 5.9: Preliminary Hazard Analysis for the power system

Discussing the results

Conducting a Preliminary Hazard Analysis is advantageous for several reasons. Firstly, it strengthens the general understanding of the system. The better the system is understood, the better foundation is obtained for making good choices throughout the design process. Secondly, the chance of hazardous events will decrease, as risk reducing measures can be implemented. Doing this in an early design phase is less resource demanding than doing it later in the process.

Two of the main problems in the Norwegian aquaculture industry is escape of fish and challenges related to health, safety and environment. The Preliminary Hazard Analysis shows that several of the hazardous events have the consequences ”escape of fish” and ”injury or death”, which underlines this statement. The component with most consequences related to injury or death of staff is the floating collar. This makes sense as the floating collar is the working area for the staff. For that reason, it is important that the design facilitates for safety. The components with most consequences related to escape of fish are the mooring system, floating collar, net and cloth. It is important that risk reducing measures are implemented in order to avoid escape in connection with these components. An example of a risk reducing measure is to design the construction with a double wall.

The Preliminary Hazard Analysis reveals that insufficient supply of oxygen often leads to the critical consequences of ”reduced fish welfare” and ”dead fish”. As mentioned earlier, a sufficient amount of dissolved oxygen in the water is important. For that reason, a well functioning oxygenation system is crucial. In addition, the importance of alarm systems and measurement devices of good quality is pointed out as crucial by the Preliminary Hazard Analysis.

The Preliminary Hazard Analysis revealed that it is beneficial to facilitate implementation of additional equipment to the system in the future. This could as an example be new digital equipment, as better technology is developed continuously. The possibility of waste collection is another example. This could be beneficial if new laws and regulations demand it in the future.

Chapter 6

Presentation of the Functions that the System must Facilitate

In this chapter, the most important functions of a closed containment system are presented. A function decomposition is carried out in Section 6.1, followed by a description of the established sub-functions. The main goal of mapping these functions is to increase the understanding of how to design the system and to discover beneficial design solutions for the customized design.

6.1 Function Decomposition

The function decomposition is based on the theory presented in Chapter 3. It is attempted to obtain a so-called optimal solution by establishing favourable functions. An effort is put in establishing adequate functions, but still, keep the number of sub-functions at a relatively low level. This is because too many sub-functions are undesirable as input to the analyzes that will be conducted in the next chapter.

The sub-functions are developed based on information collected from studying existing systems, looking into laws and regulations and by consultation with people working in the industry. Information from the Preliminary Hazard Analysis conducted in Chapter 5 was also a useful contribution.

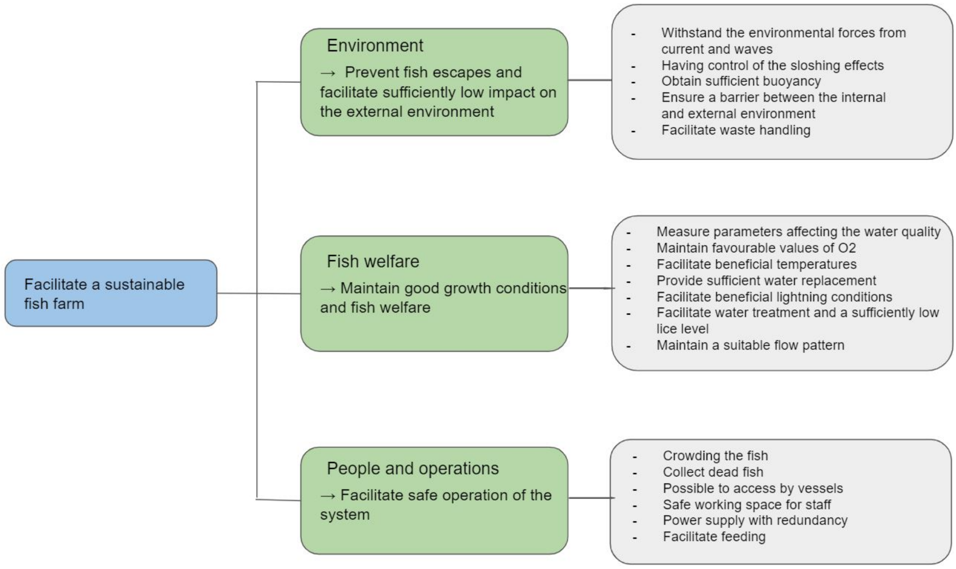


Figure 6.1: Function tree of the closed containment system

Figure 6.1 illustrates the functions established for the closed containment system. The overall function of the system is ”Facilitate a sustainable fish farm”, and is further divided into three sub-functions. These are related to ”Environment”, ”Fish welfare” and ”People and operations”. ”Environment” covers sub-functions related to preventing fish from escaping and facilitating for sufficiently low impact on the external environment, ”Fish welfare” covers sub-functions related to maintaining good growth conditions and fish welfare and ”People and operations” covers sub-functions concerning safe operation of the system.

In the following sections, each of these sub-functions will be thoroughly described. It will be focused on explaining why it is important that the system fulfils the functions, how they can be facilitated by the design and what physical effects they may include. One of the most challenging parts, which is assigned a lot of attention, is the metocean effects from waves and current, acting on the construction.

6.2 Environment

The sub-functions of the function ”Prevent fish escapes and facilitate sufficiently low impact on the external environment” will be described in this section.

6.2.1 Withstand the Environmental Forces from Current and Waves

Methodology and theory that is necessary to carry out calculations of hydrodynamic forces, from current and waves on a closed containment system, will now be discussed. Loads due to waves and current are highly influencing the construction, as most of the closed containment system is submerged. The forces from wind on the top side of the facility has a small contribution, and will therefore be neglected. A closed containment system suspected to current, incident regular waves and sloshing is illustrated in Figure 6.2. The sloshing effects will be discussed in the next function.

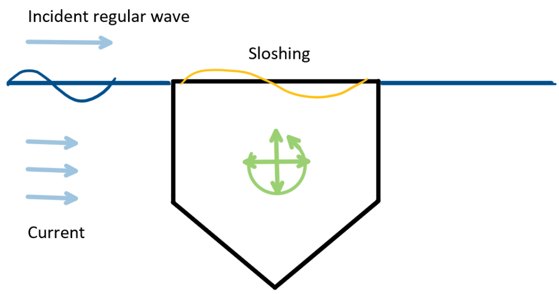


Figure 6.2: A closed containment system suspected to current, waves and sloshing.

An essential difference between the traditional fish farms and a closed containment system is that for the net-based structures, the water runs freely in and around the facility. While for the closed containment systems the internal water becomes part of the structure. This leads to a significantly increased structure mass. And hence will the forces acting on the structure become larger.

The closed containment system consists of a cloth, and is therefore highly flexible and behaves hydro-elastically which indicates that the deformation of the bag and the hydrodynamic forces are closely connected. The deformation is highly dependent on the internal and external hydrodynamic pressure as well as the dynamics of the structure (Strand, 2018). The elasticity is hard to account for when evaluating loads and motions induced by external forces. Hence, it will be assumed a rigid, non-elastic system when analysing the effect of forces from waves. When discussing the effect of sloshing, the deformation will be accounted for.

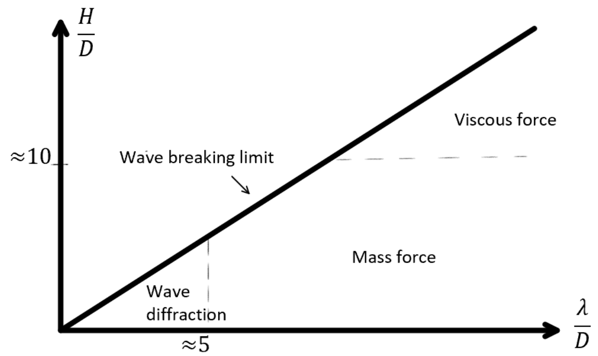


Figure 6.3: Relative importance of mass, viscous drag and diffraction forces on marine structures

Unlike a traditional fish cage, a closed containment system is considered a large volume structure (Lader, 2017). Figure 6.3 illustrated the relative importance of mass, viscous drag and diffraction forces on a cylindrical bottom based marine structures. For closed containment systems the diffraction forces are dominant. Due to the cylindrical geometry of the system this diagram can be considered a good approximation when evaluating force contributions (Faltinsen, 1990a).

First order wave loads

The first order loads results in oscillating motions in the six degrees of motions, surge (η_1), sway (η_2), heave (η_3), roll (η_4), pitch (η_5) and yaw (η_6). When calculating first order wave loads, the velocity potential will only consist of first order terms, neglecting any term of higher order (Faltinsen, 1990a). Estimating these forces requires some simplifications and assumptions.

Firstly, linear wave theory is used. It is sufficient to analyse the closed containment system in incident regular waves because by superposing results from regular waves, results from irregular waves can be obtained. Regular waves have a sinusoidal shape, and are described by the parameters shown in Figure 6.4.

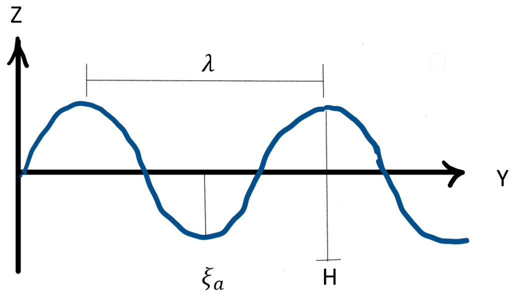


Figure 6.4: Parameters for regular waves

In order to use linear wave theory, potential flow must be assumed as well. That means that the water is assumed incompressible, inviscid and that the flow is irrotational. Also, steady state condition is assumed. It means that there is no transient effects due to initial conditions. Hence, the linear dynamic motions and loads on the structure are harmonically oscillating with the same frequency as the wave loads that excite the structure (Faltinsen, 1990a).

When analyzing both first order loads and second order loads calculations will be done for sway (η_2). This is chosen because of the importance of theses forces regarding the mooring system. The closed containment system is close to perfectly symmetric about stare board/port and fore/aft due to its geometrical shape. We can then assume that if the closed containment system is forced to move in sway, it will not move in any other degree of freedom due to the even dynamic pressure distribution along the membrane. This makes solving the Equation of motion much simpler as there is no coupling between sway and other degrees of freedom (Pettersen, 1990).

When deriving the velocity potential for deep water waves the assumptions above in addition to the boundary conditions shown in Figure 6.5 must be taken into account.

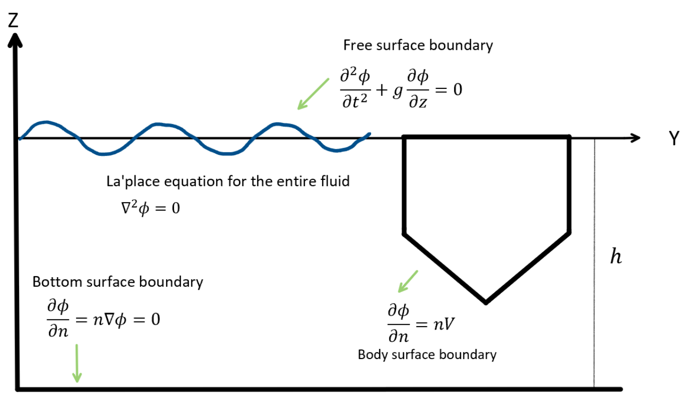


Figure 6.5: Boundary conditions

Equation 6.1 shows the velocity potential for deep water waves which is found by solving La'place equation. It is used to find horizontal and vertical velocities and accelerations of wave particles in addition to the the dynamic pressure. This is further used to calculate the wave loads acting on the structure (Faltinsen, 1990a).

$$\phi_{01}(y, z, t) = \frac{g \cdot \xi_a}{\omega} e^{kz} cos(\omega t - ky) \tag{6.1}$$

Due to the linearity of the first order loads, the total hydrodynamic force can be found from two different force contributions; the excitation forces and the radiation forces (Faltinsen, 1990a). These two forces will now be described.

Excitation

The excitation loads consists of the Froude-Kriloff and diffraction forces and moments. This is the forces and moments acting on the structure when it is restrained from oscillating and there are incident regular waves interacting with the closed containment system, as shown in Figure 6.6 (Faltinsen, 1990a).

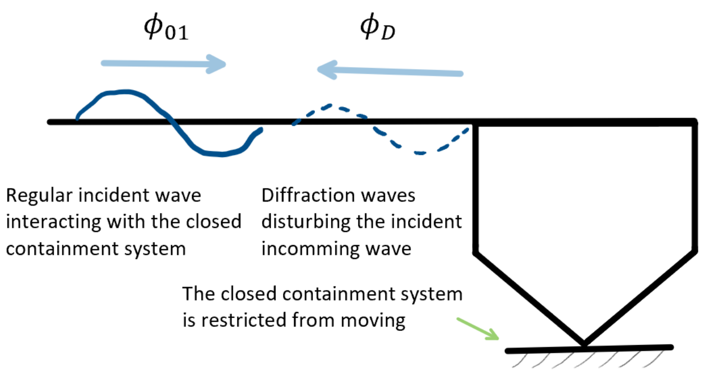


Figure 6.6: Excitation loads

The total excitation force is found by adding the diffraction force and the Froud-Kriloff force, as shown in Equation 6.2 (Faltinsen, 1990a).

$$F_{2excitation} = F_{2Diff} + F_{2FK} \tag{6.2}$$

The Froude Kriloff load comes from hydrodynamic forces induced on the body by the undisturbed incident wave creating an corresponding undisturbed pressure field and can be found by integrating the first order velocity potential using stripe theory (Faltinsen, 1990a). The force can be calculated by using Equation 6.3

$$F_{2FK} = -\int_S \rho \frac{\partial \phi_{01}}{\partial t} n_2 dS = -\int_S P_{dyn} n_2 dS \tag{6.3}$$

The diffraction load appears due to the body disturbing the incoming wave, changing the undisturbed pressure field causing diffracted waves as illustrated in Figure 6.6. The diffraction load for large volume structures is found by integrating the diffraction dynamic pressure along the wetted surface and can be calculated by the use of Equation 6.4 (Faltinsen, 1990a).

$$F_{2diff} = -\int_S \rho \frac{\partial \phi_D}{\partial t} n_2 dS \tag{6.4}$$

Radiation

The radiation forces are hydrodynamic loads connected with added mass (A), damping (B) and restoring (C) terms from the water surrounding the closed containment system. These forces occur when the closed containment system generates waves as it is forced to oscillate in the same frequency as the incoming waves (Faltinsen, 1990a), as shown in Figure 6.7. The added masse force arises from the change in pressure because of accelerated water around the closed containment system. The damping force arises when energy is transferred from the closed containment system when it is oscillating and making waves. The restoring term is closely connected to the static pressure over the wetted surface and the change in buoyance when the body is oscillating (Pettersen, 1990).

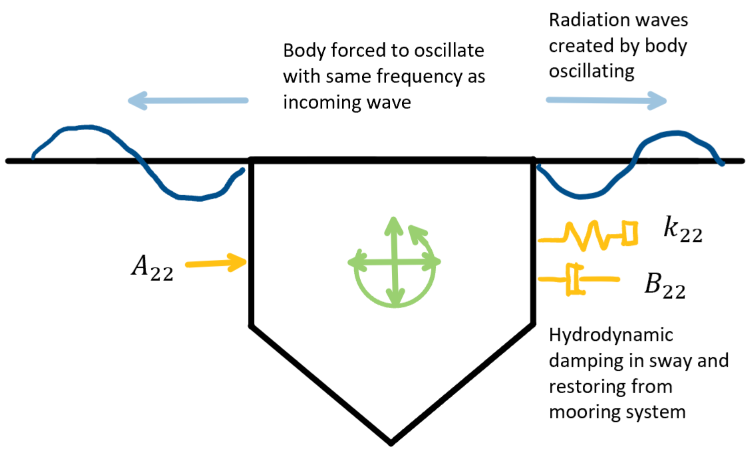


Figure 6.7: Radiation loads

The radiation force in sway is given by Equation 6.5 (Pettersen, 1990).

$$F_{2radiation} = -A_{22}\ddot{\eta}_2 - B_{22}\dot{\eta}_2 - C_{22}\eta_2 \tag{6.5}$$

Second order wave loads

Second order loads consists of mean wave drift forces, difference frequency (slowly varying forces) and sum frequency forces (high frequency force). Mean wave drift forces comes from the mean effect from the incident regular waves affecting the closed containment system. The frequency forces comes from the combined effect from different wave contributions in a irregular sea state creating high frequency and slowly varying forces. Mean and slowly varying forces are of importance in several contexts for marine structures, the design of mooring systems, with respect to the mooring line tension, is one of them. Hence, these loads are highly relevant for closed containment systems (Faltinsen, 1990b).

A irregular sea state is treated as multiple regular incident wave components. Figure 6.8 illustrates an irregular sea state presented as two regular waves acting on a closed containment system. Each wave is causing a mean drift force which is shown as a combined mean drift force, in addition to the difference frequency force and the sum frequency force.

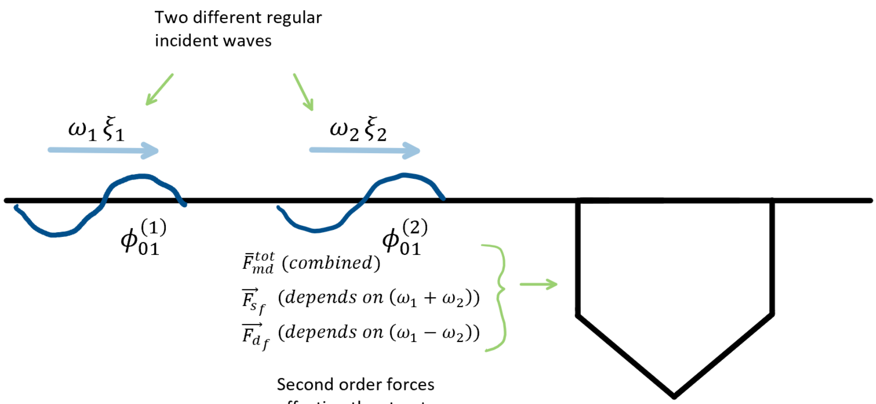


Figure 6.8: Second order wave forces affecting the closed containment system

Mean wave drift forces

Each individual regular wave in an irregular sea state exert a constant force on the closed containment system, it is from this constant force the second order mean drift arises. When estimating this forces, the assumptions are the same as when estimating first order loads. The difference is that the second order terms regarding the velocity potential must be accounted for when evaluating the pressure distribution over the wetted surface of the closed containment system. Two methods can be used for finding the loads, direct pressure integration over the wetted surface or evaluation of conservation of fluid momentum in a certain fluid volume using Maruo's formula (Faltinsen, 1990b). Only the first of these two methods will be described and used to show how the mean wave drift forces on a closed containment system can be found.

Direct pressure integration

The mean wave drift forces can be found by integrating the pressure along the wetted surface. This is done starting out with Bernoulli's equation, given in Equation 6.6 (Faltinsen, 1990b).

$$p = -\rho g z - \rho \frac{\partial \phi_1}{\partial t} - \rho \frac{\partial \phi_2}{\partial t} - \frac{1}{2}\rho \Delta\phi_1 \cdot \Delta\phi_1 \tag{6.6}$$

As the closed containment system is moored to the sea bed, we can assume zero forward speed, hence the second order velocity (ϕ_2) can be neglected. In the case of current the second order potential is important, and will be discussed later.

The closed containment system has a relatively large volume and a close to cylindrical shape. Since the wavelength is small, the body will not oscillate in the waves. From a hydrodynamic point of view, this means that we can study incident waves on a vertical wall. The velocity potential used when integrating the pressure along the closed containment system wall is shown in Equation 6.7. ϕ_{01} is the first order velocity potential expressed in Equation 6.1 and ϕ_D is the velocity potential connected with the diffracted waves (Faltinsen, 1990b).

$$\phi_1 = \phi_{01} + \phi_D \tag{6.7}$$

Assuming that the entire wave is reflected from the wall, ϕ_D becomes equal to ϕ_{01} except that it is propagating in negative y-direction. ϕ_D is shown in Equation 8.2

$$\phi_D(y, z, t) = \frac{g \cdot \xi_a}{\omega} e^{kz} cos(\omega t + ky) \tag{6.8}$$

Figure 6.9 shows a regular wave interacting with the vertical wall. Integrating the pressure contributions with the limits shown in the figure, makes it possible to obtain the horizontal drift force given in Equation 6.9. The first order velocity potential is estimated in the centre of the infinite wall, Z = 0 and Y = 0 (Faltinsen, 1990b).

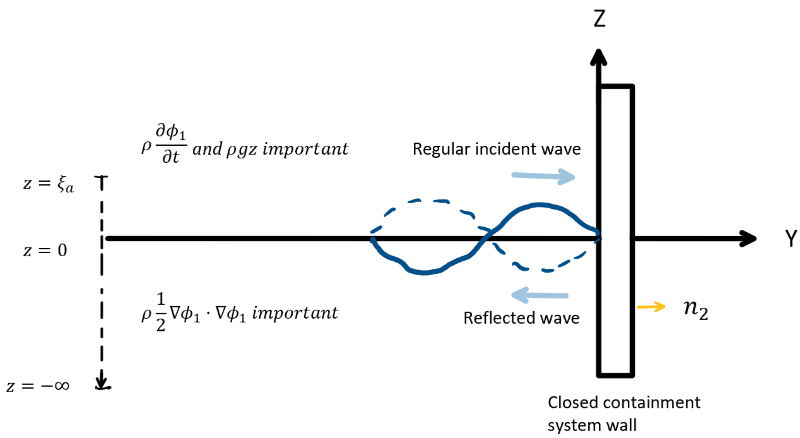


Figure 6.9: Regular wave interacting with an infinitely long wall

$$F_2 = \left[-\rho \int_{-\inf}^{0} \frac{1}{2} \Delta\phi_1 \cdot \Delta\phi_1 n_2 dZ - \rho \int_{0}^{\xi_a} \left(\frac{\partial \phi_1}{\partial t} \right|_{Z=0} + gz) n_2 dz \right]_{y=0} \tag{6.9}$$

After obtaining an expression for the drift force, the mean drift force can be found by setting the cosine or sine operators to 0 or 1, depending if it is desirable to find the maximum or minimum mean force. In this case the system should be designed for the maximum mean drift force (Faltinsen, 1990b).

Second order loads in form of mean wave drift forces is closely connected to the structures ability to generate waves. The enhanced wave generation by closed containment system compared to open traditional cages in the form of reflected and transmitted waves, will lead to enhanced mean wave drift forces. This is because of the increased mass and the solid membrane. This should especially be taken into account when designing the mooring system.

Sum and frequency forces

As illustrated in Figure 6.8 sum and difference frequency effects occur due to combined effects between different regular waves in an irregular sea state. If we consider two regular waves with the wave frequencies ω_1 and ω_2, the sum frequency effects (ω_1 + ω_2) are connected to high frequency loads. There is a chance of resonance between these oscillating force periods and the closed containment systems natural period of motion connected with vertical excitation in heave, roll and pitch. This is due to the lower natural periods associated with vertical motions for large volume marine systems (Faltinsen, 1990b).

The difference frequency effects (ω_1 - ω_2) are on the other hand connected to slowly varying loads as they are having larger periods of oscillation. Hence, the slowly varying loads are more likely to create resonance with the horizontal natural periods of the system, which is surge, sway and yaw (Faltinsen, 1990b).

There are reasons for saying that these forces have a more hidden nature than mean forces and independent wave periods. Doing an analysis of waves at a fish farm location may show that there is no danger of resonance between independent waves and the natural periods of the closed containment system. If the wave spectra is not analysed regarding slowly varying forces, this can lead to a false sense of security.

Compared to a traditional cage the horizontal natural periods are much larger for closed containment systems. The large natural period makes the structure more prone to resonance connected with slowly varying forces with high mean periods. The reason for the ibcreased natural period will be discussed below. The characteristics of closed containment systems has many similarities with large volume offshore structures, and there has been several incidents with semi submersibles where mooring line failure has occurred. Indicators points towards insufficient estimation tools and predictions regarding slowly varying forces. This shows the importance of paying attention to the slowly varying forces when designing a closed containment system (Faltinsen and Løken, 1979).

Large eigenperiod in sway

As already mentioned resonance behaviour from the interaction between wave forces (slowly varying load) and the closed containment system can lead to largely amplified forces in the system. This has to be investigated, and this will be done based on the undamped eigenperiod in the horizontal plane, more specific in the sway direction, η_2. Neglecting the damping will cause deviations from the actual eigenperiod, but is accepted due to low viscous and hydrodynamic damping (Greco, 2012). Further, it is assumed a perfectly cylindrical structure.

An expression for eigenperiod in sway can be derived from the equation of motion, assuming that the body is freely oscillating without any form of external excitation forces affecting the system as illustrated in Equation 6.10.

$$(M + A_{22})\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + C_{22}\eta_2 = F_{2excitation} = 0 \tag{6.10}$$

By performing some simple calculations and making assumptions according to *Sea loads on ship and offshore structures*, one obtain the expression for the eigenperiod, T_{2n}, expressed in Equation 6.11 (Greco, 2012) (Faltinsen, 1990c).

$$T_{2n} = 2\pi\sqrt{\frac{M + A_{22}}{k_{22}}} \tag{6.11}$$

When evaluating Equation 6.11 it is evident that an increased total structure mass (M+A_{22}) will lead to a larger natural period for the system. The added mass in sway, A_{22} is typically found from empirical data obtained from Computational Fluid Dynamics software. The software is based on the Navier Stokes Equations and simulate the flow around the structure (Hall, 2015). The added mass is a virtual change of weight of the system, and appears due to accelerated water and the following pressure change around the construction when it moves. The mooring line stiffness, k_{22}, is influenced by different parameters, but the main deciding factors are the design material and components.

Forces from current

Water particles flowing past a structure will interact with the body and induce a drag force. The drag force is known to be dependent on the shape of the structure, and the projected area, and it is caused by currents (I.M. Strand and Lader, 2016). Figure 6.10 illustrates drag forces on a cylindrical structure that occurs due to changes in the pressure field around the object when water is forced to bypass.

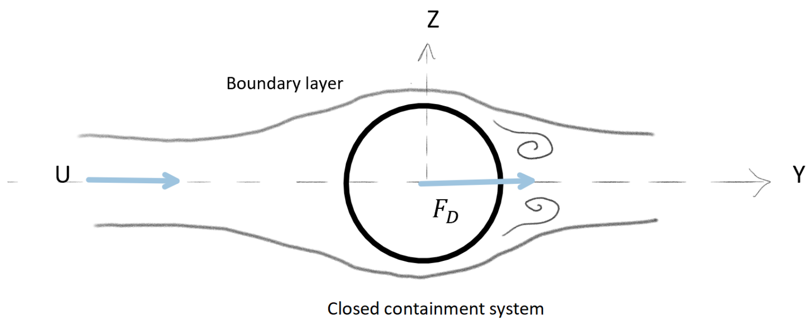


Figure 6.10: Cylindrical closed containment system in steady current

In order to estimate the drag force, Morisons equation will be used. It is assumed that the structure maintains its neutral form as illustrated in Figure 6.11, and that it is a steady, uniform current that travels in a positive y-direction.

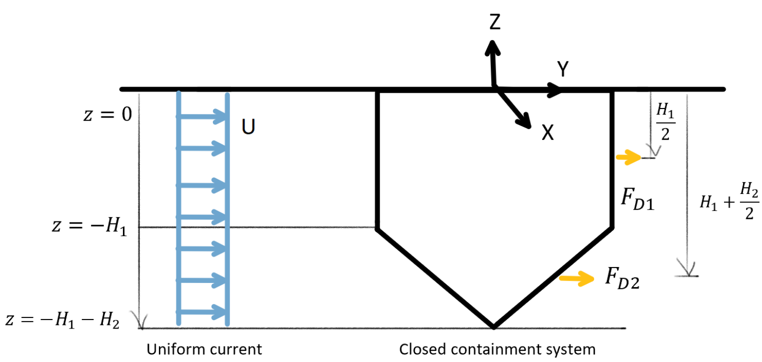


Figure 6.11: Fish farm affected by current

The Morison equation normally consists of two parts, one connected to the mass force and one connected to the drag force. When considering a uniform current with constant velocity, only the drag force is important, as the mass contribution is connected to the water particle acceleration (Faltinsen, 1990c). The drag force is expressed in Equation 6.12, where ρ is the fluid density and A is the projected area. The drag coefficient, C_D, is depending on the shape of the body, the flow regime around the body and the Reynolds number (I.M. Strand and Lader, 2016).

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{6.12}$$

As illustrated in Figure 6.11, the construction consists of two different geometrical shapes. Hence, the drag force has to be estimated in different contributions to find the total drag force. This is shown in Equation 6.13. The equation also expresses how the two contributes, F_{D1} and F_{D2}, can be calculated based on the construction illustrated in Figure 6.11.

$$F_D = F_{D1} + F_{D2} = \int_{-H1}^{0} \frac{1}{2}\rho C_D D_1 H_1 U^2 dz + \frac{1}{4}\rho C_D \pi D_2 H_2 U^2 dz \tag{6.13}$$

D is the diameter and H is the height. Using a uniform current can be very conservative if maximum values of the current velocity is used, or very non conservative if low values are used. Varying current is fully possible to account for if the variation can be expressed in mathematical terms U(z). Using the method described above gives a good initial estimation, but is prone to large deviations from the real time situation due to simplifications and assumptions. Also, if the structure is combined in a complex fish farm facility, this will affect the effect from current.

Filling level

Another aspect that is highly influential with regard to drag force from current acting on a closed containment system is the filling level. The findings of a project carried out by SINTEF Ocean on closed flexible bags, states that the drag force on a deflated bag is 1.1 to 2.5 larger than on an inflated bag (Lader, 2017). This is connected to the drag coefficient which is larger for a concave surface than for a convex surface, which is documented by different authors and stated in *Applied Fluid Dynamics handbook* by (Blevins, 1984). The drag coefficient for a concave and a convex surface is illustrated in Figure 6.12.

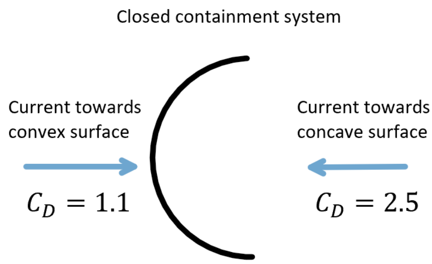


Figure 6.12: Drag coefficient for concave and convex surface

Deformation of the bag is central when it comes to filling level. An experimental study of current forces and deformations on a half ellipsoidal closed flexible fish cage, carried out by AMOS, reveals that deformation increases as the filling level and the current velocity increases. The article also states that for a 100% filling level small deformations are observed, but these deformations do not appear to effect the drag forces (I.M. Strand and Lader, 2016).

Ensuring that the system can withstand the environmental forces

NS 9415 has stated several requirements in order to ensure that a cage is able to withstand the environmental forces occurring at the specific site. Product certifications are required for some of the components and several analyzes must be performed (Standard Norge, 2009). The Norwegian Accreditation is the Norwegian body for accreditation of certification bodies, which are the companies that are approved to carry out the mentioned tasks. Aquastructures, AkvaSafe and Åkerblå are currently accredited (Norwegian accreditation, 2018).

The following analyzes must be performed and approved; a local strength analysis, a global strength analysis, a mooring analysis and a fatigue analysis. The local strength analysis provides an accurate view of the stresses around structural connections. This analysis is typically done by Finite Element Analysis (Aquastructures, 2018b). A floating aquaculture facility consists of many components and details. In addition to the loads acting on each part, the interaction between the main components and the secondary equipment must be documented. The global analysis is essential to verify that the structure has sufficient capacity (Aquastructures, 2018a). The purpose of a mooring analysis is to document that the structure of the mooring can withstand the environmental forces at the site. In addition, the analysis shall detect weak points of the mooring components, so that they can be reinforced (Aquastructures, 2018c).

6.2.2 Having Control of the Sloshing Effects

Sloshing is a phenomenon connected to the formation of an internal wave induced by external forces on a structure. The wave depends on the geometry of the structure relative to its motion and the internal water mass. This means that different waves will develop depending on the period of oscillation of the structure and the geometry. The different wave formations are referred to as eigenmodes, and are highly interesting with regards to sloshing (Faltinsen, 1990d).

The phenomenon has both structural and motional influencing effects, which can cause several problems for a structure. This includes among other things material damage and amplification of motions. In addition, sloshing can impact the fish welfare. If the system oscillates with the same period as one of the highest natural periods of the enclosed water, sloshing is of highest importance because undesired resonant sloshing behaviour may occur (Faltinsen, 1990d).

Damping of the internal fluid motions can decrease the sloshing effect. The closed containment system is made of a smooth fabric causing low friction between the water particles and the construction, and hence the viscous damping is low. If the system is designed with a net hanging inside of the cloth, some friction can however be assumed. In addition to a low damping, there is zero radiated waves, as wave radiation is impossible within a small enclosed volume (Faltinsen, 1990d).

The sloshing effects connected to a closed containment system can accordingly be high, yet there are some feature of the closed flexible structure that may contribute to reduce the phenomenon. A experiment carried out by SINTEF Ocean points out this. The experiments resulted in a report named *Sjøegenskaper og forankring til lukkede oppdrettsanlegg* and it investigates the sloshing phenomenon and its effect on different closed fish farm designs (D. Kristiansen and Aksnes, 2018). The experiments were conducted for a series of different sea-states and resulted in a plot of the Response Amplitude Operator (RAO) in surge represented by the solid line in Figure 6.13 and 6.14. The first plot is connected to an inelastic closed cage, and the second one is of an elastic closed cage. Both of the two experimental designs are cylindrical and has the same dimensions.

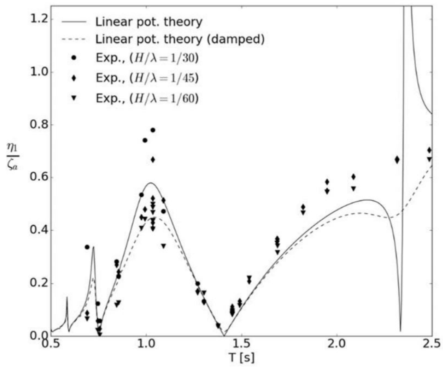


Figure 6.13: RAO in surge for inelastic closed containment system (D. Kristiansen and Aksnes, 2018).

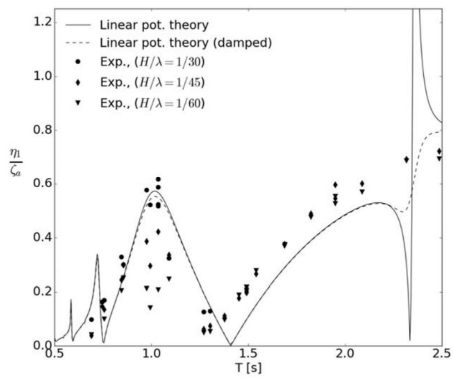


Figure 6.14: RAO in surge for closed containment system with flexible membrane (D. Kristiansen and Aksnes, 2018).

When comparing the results for the inelastic and elastic structure it shows that the RAO is somewhat lower for the elastic structure. The report states that this can possibly be due to lower sloshing amplitudes caused by membrane deformations. This means that deformation due to internal and external pressure forces interacting with the membrane may have a positive effect when it comes to amplified motion due to sloshing (D. Kristiansen and Aksnes, 2018).

The conclusion stated in the paragraph above is supported by Ida Marlen Strand, which in her Doctoral thesis informs that sloshing is highly dependent on the exibility of the membrane, and that the exibility is governed by the tension and the elasticity of the fabric (Strand, 2018). The result from the experiment from the paragraph above, also clearly indicates that free surface effects in the form of sloshing has the ability to largely influence the motion of a closed fish farm structure, in addition to availability, safety and reliability connected to it. This means that identified periods connected to significant sloshing behaviour has to be emphasized when designing the system. Also, the eigenmodes and the natural sloshing periods changes when changing the geometry and layout of the construction, which means that these has to be considered and investigated for each respective design evaluated for implementation.

6.2.3 Obtain Sufficient Buoyancy

A closed containment system must be designed with sufficient buoyancy. If this forces is not sufficiently large, the construction can in worst case sink, which again leads to large economical losses and environmental impacts if the farmed fish escapes.

Archimedes principle states that the buoyancy force is equal to the weight of the displaced water (Amdahl, 2008). The net force on an object totally or partially immersed in a fluid, is the difference between the magnitudes of the buoyant force and its weight. If this net force is positive the object rises. If negative, the object sinks and if zero, the object is neutrally buoyant. The buoyancy acts in the centre of buoyancy of the construction, and the weight acts in the centre of mass. F_b is the buoyancy force, F_w is the floating constructions weight and V is the submerged volume, as illustaated in Figure 6.15.

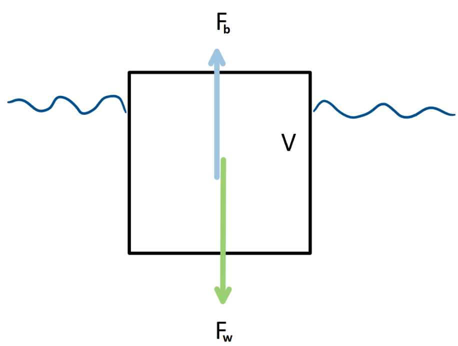


Figure 6.15: Partially submerged object

For a closed containment system, the floating collar is the component that contributes to most buoyancy. When it comes to the floatability of a closed containment system, experience has shown that there are some important factors that has to be paid some extra attention. These are as follows:

- Difference in density of the water inside and outside the cage
- The flow pattern inside the cage
- The water level inside the bag

There are density variations in the water in the water column. The differences are often larger in coastal areas where there are rivers flowing into the sea. Fish farms are often located in coastal areas and they are therefore affected by these variations. When water is pumped up from the sea and into the bag, all this water will have the same density. This leads to density variations inside and outside the bag, which again effects the floatability of the closed containment system. This must be accounted for when designing the system. The salinity can vary from one day to another at the same location, and the most extreme case must be considered (Berge, 2017a).

The flow pattern inside the bag must also be taken into account when considering the buoyancy of the closed containment system. The flow will create a force that pushes the construction down. The strength of this forces is dependent on parameters like speed and direction of the flow (Berge, 2017a).

Also the filling rate of the bag affects the pressure inside the construction, and for a closed containment system it is essential to have a higher pressure inside the cage than outside. In a worst case scenario the bag may collapse if this is not fulfilled (Berge, 2017a). The level sensor works as a guard and measures how deep down in the water the cage is located. When the water level in the bag increases, the construction sinks down, and when the water level is reduced, the cage rises. The level sensor is used to keep the cage at a desired level in the water, and if the water level is to high, the effect of the pumps are reduced and hence the amount of seawater that are pumped into the cage is reduced as well. Likewise, if the water level is to low, the effect of the pumps are increased.

6.2.4 Ensure a Barrier Between the Internal and External Environment

The main function of the barrier between the internal and external environment is to prevent fish from escaping. For flexible closed containment systems, this function is maintained both by the cloth and the net. The reason why both components are installed is because of the additional functions each of them facilitates. The net pen is used for crowding of the fish, and the cloth is the essential component for making the cage closed.

6.2.5 Facilitate Waste Handling

Fish farming contributes to local eutrophication which can harm the surroundings. This is caused by discharges from the fish and fish feed in form of dissolved and particulate organic compounds in addition to inorganic nutrients (Svåsand and Boxaspen, 2017).

The discharges are mainly a consequence of three actions. Firstly, the discharges of organic particles as faeces. Secondly, wastage of the feed, both in the form of feed dust and whole pellets which is not consumed by the fish. Finally, other inorganic compounds present in the system like dissolved nitrogen and phosphorus, which is caused by the fishs metabolism (Svåsand and Boxaspen, 2017).

Waste from fish farms is mainly a challenge regarding environmental sustainability. It is distinguished between local and regional consequences. To what extent the local environment is affected, depends on factors such as the location of the fish farm, current, waves, depth and the total amount of fish in the plant. Studies show that over-fertilized areas, in time, get reduced biodiversity. The main reason is that area demanding and fast growing macroalgaes are benefiting from the increased amount of ammonium from the fish farm. The result from this is that less sunlight reaches species with a lower growth rate. The competition for nutrition also gets tougher and therefor the least competitive species disappear (Svåsand and Boxaspen, 2017).

A consequence of the discharge of particular materials, is that it creates a sediment on the bottom. Decomposition of organic materials demands oxygen. If the supply of oxygen is to low, anoxic degradation processes start. This process produces toxic gasses that may kill demersal animals. In addition, it produces bubbles that can transport infectious materials (Svåsand and Boxaspen, 2017).

In traditional cages, it is only possible to collect a limited amount of discharge. The net is open, and particles flow out in all direction. closed containment systems on the other hand, have a great and valuable potential in collecting waste. A waste handling system can be installed in the bottom of the cage, the solid waste can be filtrated and removed from the system through a waste pipe. There are several options for how to handle the waste after removing it from the cage (Del Campo et al., 2010). One of the possibilities is to use the sludge and particles as a source of fertilizer. Fish sludge contains high levels of nitrogen and phosphorus, which is suitable for fertilizing in agriculture (Braaten et al., 2010). Removing particles such as faeces and pellets with large mesh filters, in addition to dead fish, will greatly reduce the environmental impact on the site. Hence, the time a location must be fallowed could be decreased or even eliminated.

6.3 Fish Welfare

The sub-functions of the function ”Maintain good growth conditions and fish welfare” will be described in this section.

6.3.1 Measure Parameters Affecting the Water Quality

In order to have control of the farmed environment, parameters affecting the water quality should be measured. It will now be described which sensors that are typically used for this, but first is the expression ”water quality” defined.

”Water quality” is by *Akvakulturdriftsforskriften* defined as ”the suitability of the water based on the needs of the fish, including the water's chemical (oxygen, carbon dioxide, totalammonium nitrogen, iron, aluminium, etc.), physical (temperature, turbidity, salinity and power) and hygienic (pollutants such as feedstuff, stools and fouling) quality” (Akvakulturdriftsforskriften, 2008). The regulation further states that:

§22. Water quality and monitoring
The amount of water, water quality, water flow and speed shall be such that the fish have good living conditions, based on the species, age, stage of development, weight and physiological and behavioural needs.

Water quality and between different water parameters shall be monitored based on the risk of poor fish welfare. Oxygen saturation, temperature and other water parameters that may have a significant impact on the welfare of the fish must be measured systematically.

The most commonly used sensors and monitoring gadgets in todays industry is temperature sensors, oxygen sensors, current sensors and multi sensors. Among the main suppliers of sensory technology to the aquaculture industry is AKVA group. They describe temperature as the foundation for growth and important input to feeding models. The oxygen level is an important factor for the growth and welfare of the fish, and the current sensors can prevent feed wastage due to the tidal currents that move the pellets out of the cages. The Multi Sensor is an instrument that houses six water quality sensors and measure the following 12 parameters: actual and specific conductivity, salinity, total dissolved solids, resistivity and density, dissolved oxygen, Oxidation-Reduction Potential, pH, temperature, water level and water pressure (AKVA group, 2019d).

Inge Forseth, Chief Operations Officer Software for AKVA group, states that ”digitization for the aquaculture industry is about availability of real-time sensory data, as well as developing good decision-making and analysis tools to make use of the increasing amount of information” (Jensen, 2018). He is however not the only one noticing that the Norwegian fish farm industry is experiencing a technological paradigm shift. Automatisation and exchange of data is increasingly utilized, and the shift is referred to as aquaculture 4.0, a reference to the fourth industrial revolution (Neyts, 2017). Through participation at *Brohodekonferansen 2018 - Havbruk 4.0 mot 2030*, arranged by the partners in Brohode Havbruk 2015 and NMBU, some insight in what this development may lead to was obtained. In addition to what role development of sensors played.

During the conference, expressions like big data, artificial intelligence, digital twins, internet of things and smart sensors were frequently used by the speakers when describing how the future aquaculture industry may look like. The common belief seem to be that this new technology can contribute to achieve better control of the environment, smarter decision making, increased efficiency in production and a higher safety level in the industry (Hukkelås, 2018) (Alfredsen, 2018).

6.3.2 Maintain Favourable Values of Oxygen

A sufficient amount of dissolved oxygen in the water is the most important parameter regarding production. This is because oxygen is the main limiting factor of fish metabolism and is needed for food conversion. If the oxygen level in the water becomes too low, it is first shown by reduced appetite. Over time, a reduced appetite is followed by a corresponding reduction in growth rate. The appetite gradually decreases with declining dissolved oxygen, until the dissolved oxygen reaches a level where the salmon experiences respiratory stress, and mortalities occurs. Oxygen consumption is dependent on body weight and water temperature. At higher temperatures, the fish needs higher oxygen concentration than at lower temperatures. The bigger the fish is, the less oxygen it needs per kg (Remen et al., 2016).

closed containment systems have a great opportunity of making sure that the level of dissolved oxygen inside the cage is optimal at all time. This is done by monitoring the oxygen level in addition to supplying oxygen to the water. This can be done either by adding oxygen to the water in the inlet pipe before it is pumped into the cage, or it can be supplied to the water by oxygen diffusors inside the cage. The needed oxygen supply must at all time be controlled by the control system. The oxygen source could be a liquid oxygen tank, an oxygen generator or an oxygen cylinder rack at the surface (Vard, 2018).

6.3.3 Facilitate Beneficial Temperatures

The water temperature is one of the most decisive parameters for production, as it highly impacts the growth rate of the fish (Marine Harvest, 2018). In Norway, the sea temperature varies considerably through the year depending on location, season and depth. Figure 6.16 presents the average sea temperatures in Norway and Chile through the year. It shows that in Norway the average temperature varies from about 6 °C to 15 °C. Depending on species, different temperatures are desirable for production. The Atlantic salmon is a cold-blooded animal, meaning that it is dependent on the water temperature to regulate its body temperature (Bjørnstad, 2014). According to Marine Harvest, the optimal temperature for Atlantic salmon ranges between 8 °C and 14 °C. Both higher and lower temperatures cause the growth rate to fall. Increased risk of diseases is the consequence of higher temperatures, while temperatures below 0 °C, makes mass mortality likely (Marine Harvest, 2018).

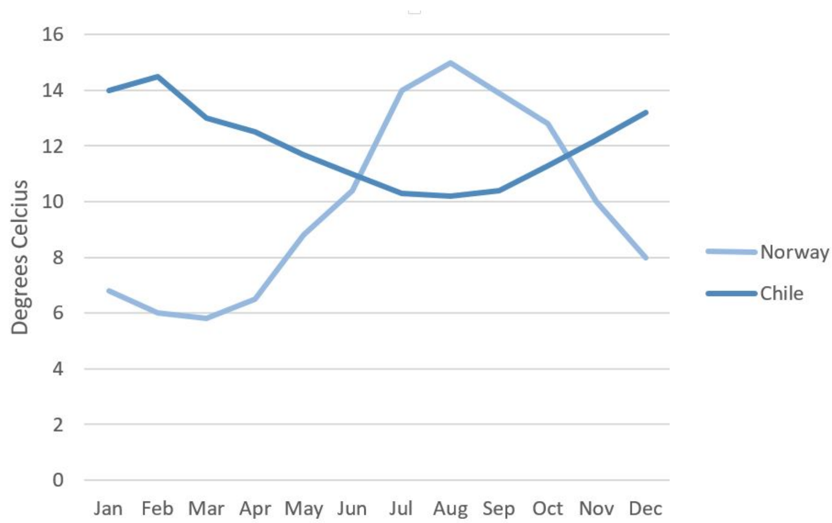


Figure 6.16: Average seawater temperatures in Norway and Chile (Marine Harvest, 2018)

Figure 6.16 shows that the seawater temperature in Chile is favourable for farming Atlantic salmon more or less throughout the year. This is a natural competitive advantage compared to other production regions, as it shortens the production time by several months (Marine Harvest, 2018). This advantage can to some extent be utilized in closed containment systems as well. The temperature of the inlet water in a closed containment system is, among other factors, dependent on the depth the water is pumped from. More stable water temperatures through the year are therefore possible to achieve. In the summertime, the water on the depth is cooler than the surface water, while being opposite in wintertime. Local variations as depth, tide and current will affect the temperatures, but compared to traditional cages, closed containment systems have the possibility of controlling the temperature of the inlet water to a greater extent (Noble et al., 2017).

The closed containment systems on today's market pumps water from different depths by the use of risers. The concept Greenbag made by Merdslippen has the possibility of pumping water from depths between 15 and 45 meters by installing risers with the desired length (Merdslippen, 2018). The Ecocage pumps water from 27 meters (Berge, 2016) and Cermaqs closed containment system delivered by Botngaard System are pumping water from a depth of 13 meters (Saue, 2018). The number of independent inlet water systems varies, but there must be more than one inlet, as redundancy is decisive. An additional opportunity is to pump water from different depths at different times. None of the concepts in today's market is exploiting this opportunity at the moment. This could either be done by using a riser that has the opportunity of being raised and lowered, or by installing several inlets on a riser with a permanent length.

6.3.4 Provide Sufficient Water Replacement

In traditional fish farms, the water inside the cages is continuously replaced as water flows through the net. As the cloth surrounding the closed containment system is impermeable, water must at all time be pumped into the cage, and flow out through designed outlets. To make sure the growth conditions inside the cage is favourable, the water quality must be stable and the water exchange rate must be customized to the production. It is also important that the water has a quality and replacement time that contributes to a stable and favourable bacterial flora (Veterinærinstituttet, 2018).

The necessary exchange rate depends on the total biomass. According to Botngaard System, a water exchange rate per kg fish should be 1 liters/minute if the total biomass is 200 tonnes and 0.6 liters/minute if it is 300 tonnes. As a rule of thumb, all water inside the cage should be replaced once an hour. To obtain the desired exchange rate, an appropriate number of inlets and effect on the inlet pumps must be decided. The cage should be designed to have excess pressure on the inside, which continuously forces water to flow out through the outlets.

6.3.5 Facilitate Beneficial Lightning Conditions

It is important to facilitate beneficial lightning conditions in the cage, as it contributes to faster growth, more effective feed utilization and prevention of fish maturation (AKVA group, 2019a). The natural lighting conditions inside a cage varies with depth, time of day, weather and season. The Atlantic salmon is most active at daytime and as is gets darker, the activity level reduces. Both surface and underwater lights should be used at night to spread the fish in the cage and to maintain its swimming activity. At winter time, high-intensity lighting should be used for 4-6 months to reduce the incidence of maturation (Noble et al., 2017).

6.3.6 Facilitate Water Treatment and a Sufficiently Low Lice Level

One of the main challenges when farming fish, has always been diseases, caused by different fish pathogens. By pathogens, it is referred to virus, bacteria or parasites (Rosten et al., 2018). By reducing the amount of pathogens that come with the inlet water, the chance of fish diseases decreases, which again reduces the amount of infectious matter in the water that is pumped out of the cage. The most problematic parasite has been the the sea lice.

The sea lice, Lepeophtheirus salmonis, is a copepod living on salmonids, particularly on Atlantic salmon, Pacific salmon and sea trout. It lives of the skin, blood and mucus of the fish. It is a naturally occurring parasite in Norwegian waters, but the volume has drastically increased as the aquaculture industry has grown (Havforskningsinstituttet, 2009). Lepeophtheirus salmonis undergoes eight developmental stages, each separated by ecdysis. The two first stages are called nauplius and the third copepodid. In these stages the lice swim around in the water, locating a host to attach to. If it can not find a host, the lice will starve. The next two stages are called chalimus, and the lice are immobile. It is attached to the salmon by a frontal filament. In the three last stages the lice are mobile, and can move freely on the surface of the host. The lice are called preadult on the two stages before it is called an adult. It is now possible to decide the sex of the parasite as well as it can move from one host to another (Havforskningsinstituttet, 2009). By Norwegian law it is specified that the maximum average amount of sexually mature female sea lice on a fish at any time is 0,5 (Luseforskriften, 2009). If the amount is exceeded, and different actions within a time limit are not able to improve the situation, the fish must be slaughtered. The farmers are required to count the amount of lice every week, and report the result to the Norwegian Food Safety Authority.

There are several reasons why the amount of lice must be held at a low level. Fish welfare is one of them. Adult lice grazing on the fish causes skin damage and lesions, which will increase the chance for secondary infections caused by bacteria and virus. The lice may also cause salt balance issues for the fish, by osmoregulatory stress. If the amount of lice becomes too high, it could be lethal. Another problem connected to the high level of sea lice in the aquaculture industry is the effect on wild salmon. It is estimated that the wild stock has decreased with 50 000 fish each year between 2010 and 2014 as a direct consequence of sea lice (Aadland, 2018). With this in mind, it is obvious that the current situation is not environmentally sustainable. There are also huge financial costs connected to this problem. It is estimated that this particular parasite costs the Norwegian aquaculture industry NOK 10 billion a year (Berge, 2017b). For that reason, the situation is not economically sustainable.

In a report published by SINTEF, three different treatment methods of the inlet water are discussed. The aim of all of them is to reduce the infection and sea lice pressure inside the cage (Rosten et al., 2018). Firstly, the inlet water should be pumped from deeper water layers. The concentration of pathogens is shown to be higher in the upper water layer. Also, the salmon lice Lepeophtheirus salmonis is mainly living in the upper 10 meters. This means that by installing pipes that pump water from below this level, the critical lice problem can be reduced. Lice skirts are utilised for the same reason (Kyst, 2018). On the other hand, there is a risk of new diseases when using water from new environments, as other pathogens are living there. Secondly, the inlet water can be filtered before it enters the cage. At the first two stages, when the sea lice swim around looking for a host to attach to, the size of it is about 0.5 mm to 0.7 mm (Havforskningsinstituttet, 2009). A parasite of that size is possible to stop from entering the cage, by using filters. Unfortunately, other viruses as the IPN virus, has the size of 60 nm and is therefore smaller. Today's filtration technology is not able to stop the small pathogens from entering the cage. The third treatment method is disinfection of the water. The most relevant technology to use is UV or el-filters. A high amount of particles in the water, will affect the efficiency of the UV treatment. Bacteria and virus could avoid the treatment by being attached to particles or other organic components. For that reason, it is beneficial to filtrate the water before a UV treatment is conducted.

Both the second and third method can be used for the outlet water as well as the inlet water. Then filters, UV equipment and el-filters must be installed at every inlet and outlet. At the moment, there are no regulation that requires that water from a fish farm should be disinfected.

6.3.7 Maintain a Suitable Flow Pattern

Suitable water flow is important considering the physical exercise of the fish and to remove waste from the cage (Veterinærinstituttet, 2018). Several factors are affecting the flow pattern inside a cage in addition to the number, direction and effect of the pumps. For example, the shape of the cage, whether there is an inside net or not, the number and placement of the water outlets and the amount of biomass inside the cage. According to a report made by SINTEF there is a reason to believe that if a sea lice manage to get inside the cage, the high water replacement and a suitable flow pattern will wash it out before it manages to attach to a host (Rosten, 2017).

6.4 People and Operations

The sub-functions of the function ”Facilitate safe operations of the system” will be described in this section. In the process of farming fish, a lot of different operations have to be carried out. Considering the fact that working in the aquaculture industry is the second most hazardous workplace in Norway, beaten only by the fisheries, it is obvious that facilitating for safe operations is of great focus (SINTEF, 2016) (SINTEF, 2018). The number of operations that is carried out on a fish farm, is high. Hence, all of them will not be described in this section, only a few, which is considered most important for the design.

6.4.1 Crowding the Fish

A crowding operation can be necessary for several situations. For example, related to medical treatment or transportation of the post smolt. Traditionally, the net pen is used for the crowding operation. There are currently no alternatives to the traditional crowding process, so that is one of the reasons why closed containment systems are installed with a net in addition to the cloth.

6.4.2 Collect Dead Fish

To maintain a good cage environment, dead fish must be removed from the cage. This is done by a dead fish collection system. The market offers several technical solutions, but the main principle is that dead fish is pumped from the bottom of the cage to the surface through a pipe (AKVA group, 2019c).

6.4.3 Possible to Access by Vessels

As workers access the cage by boat every day, and service vessels need to get moored to the cage in order to carry out their services, the design of the closed containment system must facilitate this. Pullerts and fenders make it is possible to access the cage by boat.

6.4.4 Safe Working Space for Staff

As already mentioned, the aquaculture industry is the second most hazardous workplace in Norway (SINTEF, 2016). For that reason, the work with designing a system that facilitates safety is of great importance. Rescue ladders and lifebuoys is an example of safety measures.

6.4.5 Power Supply with Redundancy

As several of the closed cage's sub-systems are depending on power to operate, a well-functioning power system is crucial. As power shortage, only for a short period of time, can lead to disastrous events, redundancy is crucial. For that reason, an emergency solution, such as a back-up generator must be installed (Johnsen, 2012).

6.4.6 Facilitate Feeding

As in all animal production, feed makes up the largest share of the total production cost. According to Mowi, feed made up 43 % of their production cost in 2018 (Marine Harvest, 2018). Hence, the feeding operation should be carried out as effectively as possible.

The feed pellets are stored in the feed barge and pumped to the cages through pipelines. It is important that the pellets are treated with caution to prevent them from being damaged and useless. To control and monitor the feeding, equipment such as cameras, lights and sensors are used. There are several types of feeding systems on the market, both underwater and surface solutions (AKVA group, 2019e).

Chapter 7

Establishing Modules

In this chapter, the final modules are established. They are obtained by conducting a House of Quality analysis and a Design Structure Matrix. The results from the analyzes are further modified and end up as 18 modules. In the last section of this chapter, the interfaces between the modules are studied.

7.1 House of Quality

The first step towards establishing the modules of the system is to conduct a House of Quality analysis. The House of Quality analysis is a versatile tool and can therefore be configured in many ways. The desired outcome of the analysis is to obtain information about which components contributing to maintaining which function, and information about the interaction between the different components.

The result of the analysis is presented in Figure 7.1. It is inspired by the theory on House of Quality presented in section 3.3, and it is configured to contain the following ”rooms”:

- **Voice of the customer:** Represented by the 18 functions established in Chapter 6.
- **Design requirements:** Represented by the 39 components presented in Chapter 4.
- **Relations matrix:** The relation matrix describes the relationship between the functions and the components. It is distinguished between an active system (A) and a partial active system (P). If the column is empty it indicates that there is no relationship between the function and the component. ”A” is assigned a component if it contributes directly to a function, and ”P” is used when a component contributes indirectly to maintain a function.
- **Correlation matrix:** The correlation matrix illustrates the interaction between the different components. If two components contribute to the same function, a high

number is obtained. The numbers range from 1 to 3. If two components, for example, contribute actively to the same function, the number 3 is filled in the "roof" of the House of Quality, meaning that they have a strong interaction. Table 7.1 shows what number different combinations of "A" and "P" lead to.

Table 7.1: Combination of relations in the House of Quality

AA	3	Strong interaction
AP	2	Medium interaction
PP	1	Low interaction

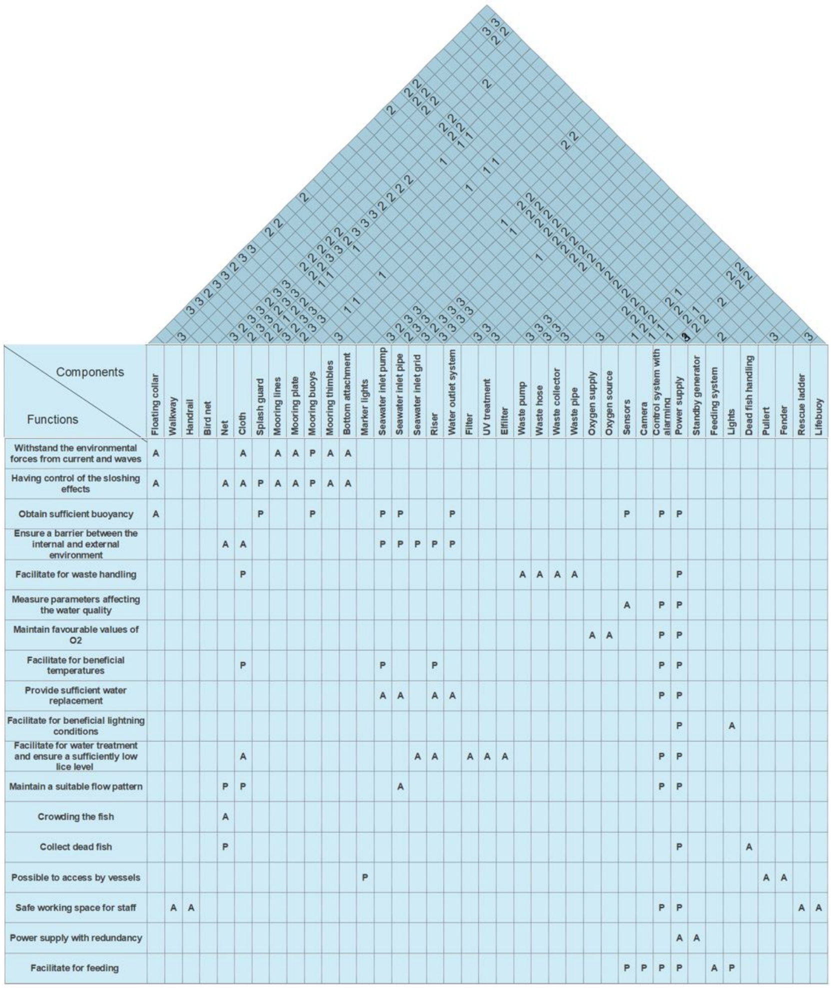


Figure 7.1: House of Quality for the closed containment system

The House of Quality presented in Figure 7.1 is made in the software Edraw Max and can also be found in Appendix 11.0.1. The room of interest for further analysis is the ”roof”. The roof shows that almost every component interacts with one or more components and that the strength of interaction is quite evenly distributed between 1, 2 and 3. The results will be used in the next section in order to perform a Design Structure Matrix.

7.2 Design Structure Matrix

Figure 7.2 illustrates the component based Design Structure Matrix. Information about the interaction between the 39 components from the House of Quality is implemented. The components are placed down the side of the matrix as row headings and across the top as column headings in the same order. A numerical interaction registration is chosen, ranging from 1 to 3. An element is left blank if there is no interaction. The diagonal elements of the matrix are blacked out as they do not have any interpretation in describing the system. The matrix is symmetric, as all interaction between components is considered interdependent.

	Floating collar	Walkway	Handrail	Bird net	Net	Cloth	Splash guard	Mooring lines	Mooring plate	Mooring buoys	Mooring thimbles	Bottom attachment	Marker lights	Seawater inlet pump	Seawater inlet pipe	Seawater inlet grid	Riser	Water outlet system	Filter	UV treatment	Elfilter	Waste pump	Waste hose	Waste collector	Waste pipe	Oxygen supply	Oxygen source	Sensors	Camera	Control system with alarming	Power supply	Standby generator	Feeding system	Lights	Dead fish handling	Pullert	Fender	Rescue ladder	Lifebuoy
Floating collar					3	3	2	3	3	2	3	3		2	2			2										2		2	2								
Walkway			3																											2	2							3	3
Handrail		3																												2	2							2	2
Bird net																																							
Net	3					3	2	3	3	2	3	3		2	2	2	2	2												2	2				2				
Cloth	3				3		2	3	3	2	3	3		2	2	3	3	2	3	3	3	2	2	2	2					2	2								
Splash guard	2				2	2		2	2		2	2																											
Mooring lines	3				3	3	2		3	2	3	3																											
Mooring plate	3				3	3	2	3		2	3	3																											
Mooring buoys	2				2	2		2	2																														
Mooring thimbles	3				3	3	2	3	3			3																											
Bottom attachment	3				3	3	2	3	3		3																												
Marker lights																																				2	2		
Seawater inlet pump	2				2	2									3	2	3	3												2	2								
Seawater inlet pipe	2				2	2								3		2	3	3												2	2								
Seawater inlet grid					2	3								2	2		3	2	3	3	3									2	2								
Riser					2	3								3	3	3		3	3	3	3									2	2								
Water outlet system	2				2	2								3	3	2	3													2	2								
Filter						3										3	3			3	3									2	2								
UV treatment						3										3	3		3		3									2	2								
Elfilter						3										3	3		3	3										2	2								
Waste pump						2																	3	3	3						2								
Waste hose						2																3		3	3						2								
Waste collector						2																3	3		3						2								
Waste pipe						2																3	3	3							2								
Oxygen supply																											3			2	2								
Oxygen source																										3				2	2								
Sensors	2																													2	2		2						
Camera																																	2						
Control system with alarming	2	2	2		2	2								2	2	2	2	2	2	2	2					2	2	2					2					2	2
Power supply	2	2	2		2	2								2	2	2	2	2	2	2	2	2	2	2	2	2	2	2				3	2	2		2		2	2
Standby generator																															3								
Feeding system																												2	2	2	2			2					
Lights																															2		2						
Dead fish handling					2																																		
Pullert													2																		2						3		
Fender													2																							3			
Rescue ladder		3	2																											2	2								3
Lifebuoy		3	2																											2	2							3	

Figure 7.2: Interactions between the components from House of Quality implemented in the Design Structure Matrix

Components that do not depend on any of the other components are removed from the matrix. These are easily identified, by having both empty columns and rows in Figure 7.2. The clustering process, where additional selection is done, is further performed. The selection is based on the following requirements:

- The interaction between the components must be evaluated as strong or medium in the correlation matrix in the House of Quality. That means that only interactions numbered 2 or 3, will be further evaluated.
- The components must be physically connected to each other. This is indicated by green colour in Figure 7.3.

The clustering process can be performed in several ways, but the main aim is the same; to find groups of components that are interconnected among themselves to an important extent, while being little connected to the rest of the system (Technical University of Munich, 2018). Figure 7.3 illustrates the modules established by the Design Structure Matrix. The modules are marked by orange squares.

	Floating collar	Walkway	Handrail	Net	Cloth	Splash guard	Mooring lines	Mooring plate	Mooring buoys	Mooring thimbles	Bottom attachment	Seawater inlet pump	Seawater inlet pipe	Seawater inlet grid	Riser	Filter	UV treatment	Elfilter	Waste pump	Waste hose	Waste collector	Waste pipe	Oxygen supply	Oxygen source	Power supply	Standby generator	Pullert	Fender
Floating collar				3	3		3						2															
Walkway			3																									
Handrail		3																										
Net	3				3																							
Cloth	3			3		2																						
Splash guard					2																							
Mooring lines	3							3	2	3	3																	
Mooring plate							3			3																		
Mooring buoys							2																					
Mooring thimbles							3	3			3																	
Bottom attachment							3			3																		
Seawater inlet pump													3		3													
Seawater inlet pipe	2											3		2	3													
Seawater inlet grid													2		3													
Riser												3	3	3		3	3	3										
Filter															3		3	3										
UV treatment															3	3		3										
Elfilter															3	3	3											
Waste pump																				3	3	3						
Waste hose																			3		3	3						
Waste collector																			3	3		3						
Waste pipe																			3	3	3							
Oxygen supply																								3				
Oxygen source																							3					
Power supply																										3		
Standby generator																									3			
Pullert																												3
Fender																											3	

Figure 7.3: The Design Structure Matrix, where the eight proposed modules are marked by orange squares

Results

From the House of Quality and Design Structure Matrix eight modules where established. The modules consist of the following components:

- **Module 1:** Floating collar, walkway, handrail, net, cloth and splash guard
- **Module 2:** Mooring lines, mooring plate, mooring buoys, mooring thimbles and bottom attachment
- **Module 3:** Seawater inlet pump, seawater inlet pipe, seawater inlet grid and riser
- **Module 4:** Riser, filter, UV treatment and elfilter
- **Module 5:** Waste pump, waste hose, waste collector and waste pipe
- **Module 6:** Oxygen supply and oxygen source
- **Module 7:** Power supply and standby generator
- **Module 8:** Pullert and fender

As discussed in Chapter 3, the process of establishing modules is not straightforward. No existing method can guarantee that the obtained modules are the optimal set of modules. Nor that the modules consist of the optimal number of components. Hence, logical thinking must be applied when evaluating and adjusting the result from the chosen modularisation method. In the next section, the final modules will be established.

7.3 Presenting the Final Modules and Their Interfaces

The list below presents the 18 final modules and the components they consist of. This section will describe the process of modifying the modules.

- **Module 1:** Floating collar, walkway, handrail and bird net
- **Module 2:** Net
- **Module 3:** Cloth and splash guard
- **Module 4:** Mooring lines, mooring plate, mooring buoys, mooring thimbles, bottom attachment and marker lights
- **Module 5:** Seawater inlet pump, seawater inlet pipe, seawater inlet grid and riser
- **Module 6:** Water outlet system
- **Module 7:** Filter, UV treatment and elfilter
- **Module 8:** Waste pump, waste hose, waste collector and waste pipe
- **Module 9:** Oxygen supply and oxygen source
- **Module 10:** Sensors

- **Module 11:** Cameras
- **Module 12:** Control systems with alarming
- **Module 13:** Power supply and standby generator
- **Module 14:** Feeding system
- **Module 15:** Lights
- **Module 16:** Dead fish handling
- **Module 17:** Pullert and fender
- **Module 18:** Rescue ladder and lifebuoy

Considerations made when modifying the modules

Several considerations must be kept in mind simultaneous when establishing the final modules. This can make the process somewhat complicated to perform. To simplify the process, the most important considerations are highlighted. The list below contains these considerations and serve as support for decision making:

- It is desirable to establish ”function modules”, which means that all components of a module should collaborate on fulfilling the same function.
- It is desirable with as low interconnection between the different modules as possible.
- It is advantageous if all components in a module are supplied by the same company.
- The components within a module should normally have a physical connection, but this is not a demand.

The work on establishing the modules can be viewed as an iterative process as several attempts were made before ending up with the final result. In the following paragraphs, the changes within each module will be reasoned. The components that were left eliminated from the Design Structure Matrix analysis, because they did not interact with any of the other components, are now brought back and included in a suitable module.

Modification of the modules

Module 1 from Section 7.2 is divided into three different modules. This is done despite the fact that all components are physically connected to each other. The reason why it is done is that they serve different functions and are supplied by different companies. The floating collar, walkway, handrail and bird net poses one new module, the net poses another module and the cloth and splash guard constitute a third module. The bird net was left out of the Design Structure Matrix analysis because it did not interact with any of the components, but are not included in a model that it shares the same dimensions with.

Module 2 from Section 7.2 is unchanged, except that marker lights are added. This is done to gather all the components that make up the mooring system in one module. Module 3 is also kept unchanged as all the components serve the common function of providing inlet water to the system.

The riser ended up in two different modules in section 7.2, and is therefore removed from module 4. This is done because even though all components in the original module serve the function of ensuring a sufficiently low lice level, the riser and the rest of the components facilitate the function in different ways. For that reason, the design of these components are not dependent and shall not be in the same module. Module 5, 6, 7 and 8 from Section 7.2 are all kept unchanged.

The modification of the 8 original modules is now explained. Some additional modules are also added, which mainly consist of components only depending on one or none of the other components in the system.

Interfaces

As discussed in Chapter 3 modular product architecture is a form of product design that uses standardised interfaces between modules to create a flexible product architecture (Sanchez and Mahoney, 1996). Well-functioning interfaces are crucial for the unit to work as planned when all modules are being connected.

The type of modularisation used for this system is ”Slot modularity”. The interfaces in slot modularity are specific for each module, meaning that the interfaces for all the modules are different from each other. Hence, there is only one way of connecting the modules to each other (Ulrich, 2008). ”Bus modularity” and ”Sectional modularity” was not found beneficial as they are characterised by using similar interfaces for several of the modules.

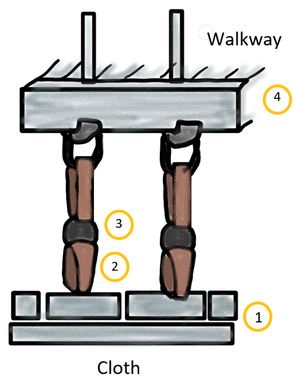


Figure 7.4: Interface between the cloth and the floating collar

An example of the interface between two modules is given in Figure 7.4. It shows how the floating collar from module 1 and the cloth from module 3 are connected. Clamps (1) are attached to the cloth and shackles (4) are welded to the floating collar. A strop (2) and a damping block (3) is used to connect component (1) and (4). The interface is inspired by a connection system Botngaard System are using. Standardised interfaces facilitate the possibility of replacing modules independently, and the whole system does not need to be replaced if one component gets destroyed.

Chapter 8

Developing a Simple Tool for Proposal of a Customized Design

The work until now has focused on obtaining inside knowledge of closed containment systems, its components and on design theory. In this chapter, this information will be utilized to develop a simple tool for proposal of a customized closed containment system.

8.1 Presenting the Standardised Modules

The customized design is based on the set of modules presented in the previous chapter. In order to propose a customized design, it must be established a solution space within each of these modules with several options to choose between. Table 8.1 presents the solution space within each of the modules. The table includes information about which components each module consist of, choice of concept, dimensions of the components, quantity and other characteristics like material and strength. In the cells with the sign ”-”, no information is given as it is considered excess information, the answer is viewed as intuitive or irrelevant for further work.

An evaluation of which components within each module that should be standardised and which should be customized in each delivery, will also be given. Professor Jan Ola Strandhagen has informed that no existing method is able to determine whether a component shall be standard or not, and hence the decision must be based on the designer's knowledge and experience. In the table, the standard deliveries are represented by the cells only containing one solution, while the once with several options, are modules possible to customize. As the table shows, a lot of the components ended up as standard in all deliveries.

An explanation of the expression ”standardised modules” will now be given. The overall objective of this thesis is to develop inside knowledge for the design of a customized closed containment system, based on standardised modules. These standardised modules are the once presented in this section. They are called standardised because all deliveries will contain the same modules, and even though the alternatives within the solution space offers different variants of the modules, the unique interface facilitates for a standardised connection to the rest of the system.

Table 8.1: Presentation of the solution space within each of the moduls

Component	Concept	Dimension	Characteristics
Module 1			
Floating collar	16-edged floating collar made out of 16 hollow modules, that are welded together	Circumference: 120 m Outer length/width 41.6 m Diameter: 1420 mm Thickness: 12.5 mm Length each element: 8 m	Material: Steel Number: 1
Walkway	-	Circumference: 120 m Width: 1.5 m	Material: Steel Number: 1
Handrail	-	Circumference: 120 m	Material: Steel Number: 1
Bird net	Fiberglass support poles	Height: 5m	Material: Fiberglass poles and nylon net Number: 1
Module 2			
Net	Cylindrical shape	Depth: 19 m, 22 m or 24 m Circumference: ca 120 m	Material: Nylon Mesh opening: 30.4 mm Solidity: 0.19 Breaking strength 96 kg Number: 1
Module 3			
Cloth	Cylindrical elastic cloth	Circumference: 120 m Depth: 20 m, 23 m, 25 m	Material: Biobrane Aqua 2050 from Serge Ferrari Weight: 2250 g/m^2 Tensile strength (warp/weft): 1300/1300 daN/5cm Tear strength (warp/weft): 150/300 N Number: 1
Splash guard	16 cloth sections connected to the cloth	Circumference: 120 m	Material: PVC Number: 1
Module 4			
Mooring lines	-	-	Material: Fibre rope/steel chain
Mooring plate	-	-	Material: Steel
Mooring buoys	Buoy with reflector discs	-	Material: PE filled with polystyrene foam
Mooring thimbles	-	-	Material: Steel
Bottom attachment	Drag anchor, bolts or piles	-	Material: Steel
Marker lights	Integrated GPS and solar panel	-	Battery life time: 18 months
Module 5			
Seawater inlet pump	Pumps having blockage at outlets	-	Effect: 20 kW, 25 kW and 30 kW Number: 4
Seawater inlet pipe	-	Diameter: 900 mm	Material PE Number: 4
Seawater inlet grid	-	-	Mesh opening: 20x20 mm Number: 4
Riser	One or two water inlets	Length: 16 m Diameter: 1200mm	Material: PE Number: 4

Component	Concept	Dimension	Characteristics
Module 6			
Water outlet system	Excess pressure inside the cage forces the water out throug the outlet valves	-	Material tube: PVC Number: 10
Module 7			
Filter	-	-	Number: 0 or 4
UV treatment	-	-	Number: 0 or 4
Elfilter	-	-	Number: 0 or 4
Module 8			
Waste pump	-	-	Number: 1
Waste hose	-	Diameter: 150 mm Length: 29 m, 31 m and 35 m	Number: 1
Waste collector	-	Diameter: 2500 mm	Number: 1
Waste pipe	Collecting the waste or dump it back in the sea	-	Number: 1
Module 9			
Oxygen supply	Diffusor hoses inside cage	-	Number: 6, 7 or 8
Oxygen source	Oxygen tank or oxygen generator. Additional backup source	-	Number: 1
Module 10			
Sensors	Measures: oxygen temperature salinity water level multi sensor	-	Number: 2 inside cage, 1 outside 1 inside cage, 1 outside 1 inside cage, 1 outside 4 inside cage 1 inside cage
Module 11			
Cameras	Tilt colour camera Both under water and on surface	-	Number: 6
Module 12			
Control system with alarming	AKVA Observe AKVAconnect Fishtalk Control Fishtalk Equipment	-	Number: 1
Module 13			
Power supply	Powerline or diesel generator	-	Number: 1
Standby generator	diesel generator		Number: 1
Module 14			
Feeding system	AKVAsmart CCS feed system	-	Number: 1
Module 15			
Lights	Under water lights	-	Material: LED Effect: 510 W Number: 6
Module 16			
Dead fish handling			Capacity: 500 kg/hour Number: 1
Module 17			
Pullert	-	-	Number: 4 x 4
Fender	-	-	Number: 4 x 6
Module 18			
Rescue ladder	Installed on gangway with cover	-	Number: 8 Capacity: One person
Lifebuoy	-	-	Number: 2

8.2 Describing the Solution Space Within Each Module

A description of the solution space and characteristic for each of the 18 modules, given in Table 8.1, will now be given. It includes choice of concept, dimensions of the components and other characteristics like choice of material. The Preliminary Hazard Analysis provided information regarding the overall risk picture of the closed containment system and proposed mitigating measures. Some of these proposals will now be discussed and benefited from in order to make a safer design. The establishment of functions revealed possible design solutions. These will also be discussed and benefited from in this section. Also, some alternative design solutions will be evaluated.

Module 1 - Floating collar, walkway, handrail and bird net

The main function of the floating collar is to give the construction the necessary buoyancy, as well as maintain the volume of the net. It should be designed in a way that makes it easy and safe to walk around on, as well as doing inspections and other work. The floating collar is one of the main components of a closed containment system. For that reason, the concept type chosen for this component is essential for the characteristics of the whole system. Hence, several alternatives were evaluated before deciding on the concept.

It is distinguished between three framework concepts; a stiff framework, a stiff framework with movable joints and a flexible framework. The main difference between these alternatives is their ability to handle forces from waves. A stiff framework is not able to follow the movements of the waves in the same way as the other two alternatives. As a result, more forces will be taken up by the framework. Further, this makes the stiff framework less suitable for exposed locations (Kumar and Karnatak, 2014). Several shapes of the floating collar were considered, both circular, rectangular and polygonal shapes. Circular shapes have several advantages compared to rectangular shapes. Based on the swimming behaviour of the fish the space inside the cage is better utilized. Further, the cost-volume ratio is more beneficial as a greater volume can be obtained by using the same amount of material. It is also more resistant to dynamic stress as the forces are equally distributed around the circumference. For rectangular frameworks, the force will be concentrated in the corners. As polygonal collars have more corners than rectangular collars, the load in each corner is reduced (Kumar and Karnatak, 2014). Cages can be made out of a variety of materials like high-density polyethylene, polyvinyl chloride, galvanized iron, aluminium, steel, timber and other plastic materials. When selecting material several aspects must be considered; the strength of the material, resistance against corrosion, price, availability and maintenance opportunities some of them (Kumar and Karnatak, 2014). In the traditional Norwegian fish farming industry, the most used materials are steel and high-density polyethylene. Pipes made of high-density polyethylene has been used on a large scale for transporting gas and liquid in the oil industry and is therefore widely available. The material has several beneficial characteristics, they are durable, flexible, shockproof, resistant to ultraviolet light and require little maintenance, as long as they are installed correctly. Steel, on the other hand, is a stronger material, that can handle rougher treatment. The availability of this material is good as well (Cardia and Lovatelli, 2015).

The chosen concept is a 16-edged floating collar made out of 16 hollow steel modules that are welded together. As this is a stiff framework, the chosen shape is beneficial as it distributes the forces on a high number of corners. The circumference of the floating collar is set to 120 meters and as it is physically connected to the walkway, handrail and bird net it determines the dimensions of these components as well. The Preliminary Hazard Analysis carried out for the floating collar revealed several hazardous events and the mitigating measures for three of them will now be presented. In order to mitigate the risk of the hazardous event ”Vessel or other external force making a hole in the floating collar, which leads to healing” with the possible consequence ”Escape of fish” is taken into account by dividing the construction into several bulkheads. Further, in order to mitigate the risk of another hazardous event related to corrosion of the floating collar, several anodes are mounted on the floating collar. The risk-reducing measures implemented to avoid the hazardous event ”Staff falling into the sea” is to install handrails all along the floating collar. Both these and the walkway is made of steel.

The decision of keeping this module standard in all deliveries is of great importance for the final design result as it is one of the systems main components. An advantage from supplying the same floating collar in all deliveries is that the component is already certified, and both time and money are saved as this not need to be done for every delivery. A disadvantage from this is that as the component is certified for a given environmental load, it will limit the possible locations for the cage. If the site survey shows higher environmental loads than what the component is certified for, the closed containment system cannot be placed there. Another disadvantage is that the component is oversized for the smallest volumes as it must be designed to provide sufficient buoyancy for the largest construction. This is however not viewed as very problematic, because the supplied constructions demand approximately the same buoyancy. This is because the varieties of the weight of the different constructions are not so large, as the size range of the supplied volumes is limited. The size range will be presented in the next module.

Module 2 - Net

First it will be explained why it is decided to make the net a basic module for the construction. Because, for a closed containment system, it is not obvious that a net must be included in the design. This is because the cloth functions as a barrier between the fish and the sea, and therefore a net do not necessarily ned to be included as this is also the main function of the net. The results from the Preliminary Hazard Analysis revealed several reasons for including the net. In total, four hazardous events had the risk reducing measure ”Net inside the cloth”. Also if any of the following hazardous events; ”Power shortage”, ”No oxygen supply”, ”Pumps does not work” and ”Sensory system does not work” happening, the net is found useful. This is because it is suggested, as a last option, to cut the cloth in order for fresh water to flow into the cage and avoid that the fish from dying of lack of oxygen. A final argument for including the net is that the function ”Crowding the fish”, depends on a net.

The characteristics for the net is the same in all deliveries. It is supplied by Mørenot and made of nylon. Nylon is the desired choice of material as it has a high tensile strength relative to the thickness of the line and its weight. In addition is it resistant to UV radiation

(Mørenot, 2018). The mesh opening is 30.4 mm, which is small enough for the post smolt not to get through the net. Also, it is not necessarily to change the net throughout the production period, which is positive from an economical point of view. The solidity, which is the area covered by netting material divided by the area of netting panel, is 0.19. This number is always between 0 and 1 (Føre, 2017).

Several net shapes were considered before selecting the cylindrical one. This includes a square net, cone net and a spaghetti net. Figure 8.1 illustrates the selected shape. The upper part of the net is cylindrical, and the lowermost part is conical. The angle of the lowermost part should be between 30°- 45°. A steep angle is beneficial to make the waste go to the bottom of the cage, where the waste collector is located. A steep angle will also make the conical part larger. It is undesirable to make this part too large, as it is shown that the water circulation is less beneficial in a cone shaped part. Hence, an angle of 40°is selected. This evaluation is based on Botngaard Systems experiences.

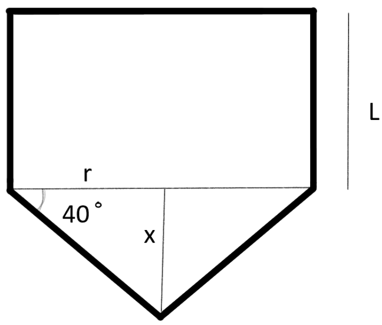


Figure 8.1: Shape of the cage and symbols used to calculate the volume

The dimensions of the net depends on the volume of the cage. Several size steps are therefore included in the solution space of this module. The size range and step is selected based on the information provided on this in Section 3.2.6. Among other factors, the choice depends on the market situation. Based on Botngaard System's experience, closed containment systems used for on growth of post smolt are mostly demanded in the volume ranging from 10 000 m^3 to 15 000 m^3. It is decided to supply three volumes within this range.

The total volume of the cage depends on the circumference, shape and depth of the net. Both the shape and circumference is standard in all deliveries, so the volume is determined by the chosen depth of the net. The reason for having two constant parameters and one variable, is to facilitate for making standardized components and modules. This is often beneficial both regarding cost, lead time, experience and maintenance. The total volume of the cage can be calculated by Equation 8.3. The symbols used in the calculation are shown in 8.1. The circumference of the net is 120 meters in all deliveries. Further, it is decided to offer three net depths, which is presented in Table 8.2 along with the corresponding volumes.

$$Volume = \pi * r^2 * (l - x) + \frac{\pi * r^2 * x}{3} \tag{8.1}$$

Table 8.2: Depth on net and corresponding volums

Depth of cloth [m]	Volume [m^3]
19	9 500
22	12 900
24	15 300

Module 3 - Cloth and splash guard

The impermeable cloth participate in fulfilling several of the functions of the system. This includes ”Facilitate waste handling”, ”Facilitating for water treatment”, ”Maintain favourable values of O2” and to ”Ensure a barrier between the internal and external environment”. The cloth makes it possible to control the water quality inside the cage, and reduce the impact the system has on the external environment.

The shape of the cloth is similar to the shape of the net, and the circumference of both the cloth and the splash guard is similar to the dimension of the nets circumference. As can be seen from Tabular 8.1, are the shape of the cloth cylindrical, the circumference of the cloth is 120 meters and there are three depths available. As the cloth is placed outside the net, the depths are slightly larger than for the cloth. The circumference of the splash guard is also 120 meters, and it consists of 16 cloth sections made of PVC that are connected to the cloth. When it comes to the material of the cloth, a flexible material was picked. Several alternatives were evaluated before ending up with a cloth type that is both used by Botngaard System and Ecomerden. The Biobrane Aqua 2050 cloth supplied by Serge Ferrari is beneficial because of the strength versus weight ratio, the flexibility of the material, and its long lifetime (Ecomerden, 2018b). Additional characteristics of the cloth material is given in Table 8.1.

Module 4 - Mooring lines, mooring plate, mooring buoys, mooring thimbles, bottom attachment and marker lights

According to NS 9415 the mooring shall keep the fish farm in a correct position (Standard Norge, 2009). Two of the most important functions the mooring system must fulfil is, according to the functions established in Chapter 6, to ”Withstand the environmental forces from current and waves and to ”Have control of the sloshing effects. In order to do so, it must be designed based on the environmental conditions at the site.

To establish a clear relationship between the forces acting on the construction and the needed layout and geometry of the mooring is not straightforward. It is important to know the closed containment systems natural period of motion, as it is a chance of resonance between this and the oscillating forces periods. As the eigenmode changes when changing the geometry and layout of the construction, it has to be considered and investigated for each respective design evaluated for implementation. To develop a solution space for the module did hence turn out to be more challenging than for the other components. A decision of customizing the mooring system for all deliveries was therefore made. This decision is supported by NS 9415, where it is stated that all main components except from the mooring system must be product certified. The mooring system should be designed by a company or a person that is certified, and a customized design must be made for each delivery (Standard Norge, 2009) (Fiskeri- og kystdepartementet, 2005).

Suggestions to dimensions of the mooring system will therefore not be given, but some other characteristics can however be standardised. They will now be described. The upper length of the lines are made of fibre and the lower end is a chain section (Kumar and Karnatak, 2014). The mooring plates are made of steel and connects the rope that surrounds the fish cage to the floating buoys at the surface and the anchor lines (Chakrabarti, 2005). Mooring buoys are buoyancy elements used to manage vertical forces in the mooring system. They are made of a plastic material, polyethylene, and are filled with polystyrene foam (Kumar and Karnatak, 2014). Typical connectors that are used in mooring systems are thimbles and shackles. The connector is design to take the maximum breaking load of the mooring lines it is connected to (Chakrabarti, 2005).

There are several types of bottom attachments used in mooring systems, each suitable for different bottom types. Drag anchors are dragged down into the ground and becomes fixed, and are therefore suitable for sand bottom. Bolts can be used to fasten mooring lines to rocks and are therefore used for rock bottom. Piles are suitable for clay bottoms (Kumar and Karnatak, 2014).

Module 5 - Seawater inlet pump, seawater inlet pipe, seawater inlet grid and riser

The closed containment system will be installed with four units of this module. The main function of this module is to provide sufficient water replacement, a function that is crucial in order to maintain good fish welfare. Due to the importance of the function, it was decided to choose a design concept that is already used by a number of actors on the market, instead of testing out a less familiar one. By conducting the Preliminary Hazard Analysis, information about several hazardous events concerning the pump was obtained. Fish escaping through the pumps at start up is considered the event with the most critical consequence, and hence blockage of the outlets was added to the concept of the pumps. The concept of the riser is optional, as the customer can choose whether to have one or two water inlet. An inlet at the depth of 10 meters can be added in addition to the inlet at the depth of 16 meters depth. As the water temperature changes through the water column, this gives a opportunity of pumping water from the most desirable height. As known, the water temperature affects the growth of the fish, and hence it can be desirable for the farmer to have this possibility from an economic point of view.

The dimensions of the module can be found in the Table 8.1. One of the most important dimensions is the length of the riser, which is set to 16 meters. The reason why this length was decided on will be given now. One of the functions the riser is facilitating is to ensure a sufficiently low lice level. As discussed in Section 6.3.6, a common view among fish farmers is that the sea lice is staying in the 10 upper meters of the sea. Therefor, the water that is pumped into the cage shall be collected from depths beneath this. Further, seen from a hydrodynamic point of view, the longer the riser the more forces will act on the body. Due to this, a too long riser is undesirable. Based on these two considerations, the length of the riser is set to 16 meters.

The desired rate of water exchange sets the base for the pump characteristics. Based on advice from Botngaard System, presented in Section 6.3.4, a water exchange rate for the water inside the cage was set to one hour. Hence, three pump effects of 20 kW, 25 kW and 30 kW are offered, depending on the total volume of the cage. An advice that will be given to the customers is that if they choose to implement the optional module 7, they should decrease the exchange rate in the early stage of production. This is because when the biomass in the cage is still low, it is not necessarily with such a high water exchange rate. The reason why this is beneficial for the farmer is that the filters and UV treatment demand a lot of power which is expensive. The dimensions of the grid on the pumps are sufficiently small so that fish is not able to escape through the meshes.

Module 6 - Water outlet system

The main function of the water outlet system is to transfer the same amount of water that flows in to the cage, out again. Water flows through the valves when it is excess pressure inside the cage. The module contributes to maintain several other functions too; ”Provide sufficient water replacement”, ”Obtain sufficient buoyancy of the system” and to ”Ensure a barrier between the internal and external environment”. The valves are equipped with a grid so that the fish can not escape through them.

The water outlet tubes are made of PVC, which is a strong and relatively light material. In all deliveries ten of this module is installed, a number that is selected based on experience made by Botngaard System.

Module 7 - Filter, UV treatment and elfilter

Module 7 is the only optional module in the system. This means that the customer can choose rather to include the module or not. Today’s regulations do not require any kind of filtration or treatment of the water pumped in and out of the cage. This is reasonable, as it is impossible to implement for traditional open fish cages. It is on the other hand possible for closed containment systems, and it is therefore desirable to facilitate. The advantages of disinfecting the water is discussed in Section 6.3.6.

The module is mounted on the water inlet system. Therefore will the same number of module 7 as module 5 be supplied to the customer. Even if the customer chooses not to implement the module, the design facilitates for later upgrades.

Module 8 - Waste pump, waste hose, waste collector and waste pipe

The main function of module 8 is to collect waste. A short description of how the chosen concept works, will be given. Waste from the salmon production sinks down into the waste collector, which is located in the bottom of the cloth. A waste hose is connected to the bottom of the waste collector, which again is connected to a submersible waste pump. The system do in this way facilitating for pumping the waste up to the surface.

Two different concepts are available when it comes to handling the collected waste. The first one is to use the waste as a source to fertilizer, and the second and most common one, is to filter the waste and remove it from the site through a waste pipe. Both concepts leads to reduced impact on the environment. Therefore, the time the location must be fallowed can potentially be reduced or even eliminated for this type of system compared to traditional ones. The two options are described in detail in Section 6.2.5. The farmers preferences determine which concept that shall be used but they are encouraged to base the decision on considerations of the local environment, bottom conditions, currents, waves, depth and the biomass of fish in the cage.

All dimensions are similar in all deliveries, except from the length of the waste hose that are adjusted to fit the depth of the cloth for every delivery. The three available lengths are 29 meters, 31 meters and 35 meters. Equation 8.2 shows how the length is calculated for a cloth of 19 meters.

$$L_{hose} = (19m - x) + \frac{r}{cos(40)} = 19m - \frac{\frac{60}{\pi}}{cos(40)} \cdot sin(40) + \frac{\frac{60}{\pi}}{cos(40)} = 28m \quad (8.2)$$

The length is found from adding the vertical length of the cylindrical part of the cloth to the length of the hypotenuse of the coned part. One additional meter is added to the length in order to create some space between the cloth and the hose. The radius is denoted r and the depth of the conical part is denoted x, as illustrated in Figure 8.1.

Module 9 - Oxygen supply and oxygen source

Closed containment systems have the great opportunity of making sure that the level of dissolved oxygen inside the cage is beneficial at all times. But, being dependent on continuously supplying oxygen to the water comes with a risk. Hazardous events such as power shortage, empty oxygen source or destroyed oxygen equipment are revealed in the Preliminary Hazard Analysis. These events may lead to bad fish welfare or death. For that reason, risk reducing measures must be taken into account. Having sensors and a well functioning sensory system with alarms that detect abnormal behaviour is one of them. Further, two types of oxygen sources are available, either an oxygen tank or an oxygen generator. For the oxygen tank, a pressure sensor is installed inside it to give a warning before the tank is empty. The oxygen generator is in most cases the preferred option as this is a cheaper option in the long term, despite a higher CAPEX (Vard, 2018). Finally, a backup oxygen source is available.

Several oxygen supply concepts were considered. One of them was supplying oxygen to the inlet water before it enters the cage, which is done in the Ecocage (Ecomerden, 2018b). But, the concept that is chosen to use for all deliveries is diffusor hoses inside the cage. Depending on the volume of the cage, 6, 7 or 8 hoses are installed in the bottom of the cage. This decision was based on information obtained from experience made by Botngaard System. The oxygen level in the cage is automatically regulated by the control system.

Module 10 - Sensors

The main function of this module is to measure parameters affecting the water quality. As stated in Section 6.3.1, parameters affecting the water quality shall be measured systematically. For this, a oxygen sensor, temperature sensor, salinity sensor and the multi sensor is used. The information from the sensors are used to monitor the feeding prechosen concept for this module as well.

AKVA group is chosen as the supplier of the sensors as they are the main supplier of sensory technology to the aquaculture industry (AKVA group, 2019d). The level sensors function is to monitor the water height to make sure that the cage has sufficient buoyancy. The chosen concept for performing this function is by hanging the level sensors from the floating collar and down in the sea to measure how deep in the sea the cage is located.

The characteristics selected is based on experience made by Botngaard System. It is decided to deliver all systems with the same number of sensors. Two O2-sensors are installed inside the cage and one outside, one temperature sensor is installed on the inside and one on the outside, one salinity sensor is placed on the inside and one on the outside, four water level sensors are placed on the inside of the cage and one multi sensor is installed on the inside.

Module 11 - Cameras

A number of different cameras are available on the market. This included all from basic fixed monochrome and dual tilt colour cameras to advanced IP surveillance cameras. The field of application spans wide and include among others things feeding control, biomass estimation, and surveillance (AKVA group, 2019d). It is decided to offer six of the tilt colour camera to all customers as it covers the essential needs for all uses.

Module 12 - Control system

Based on information from the sensors and cameras, the control system can provide the farmer with huge amounts of information. A number of different concepts are available on the market. AKVA group is among the leading suppliers of software and hardware solutions to the fish farm industry. For the farmers who desire ”full overview and control”, they can offer the following solutions: AKVAconnect, Fishtalk Control, Fishtalk Equipment and AKVA Observe. AKVAconnect is a powerful Supervisory Control And Data Acquisition process control platform used to connect and control a wide range of equipment and technical processes at the farm. Fishtalk Control provides a complete overview of the biological status. The software consists of various modules that are easily combined to meet the farmers needs. Fishtalk Equipment organizes all the farming equipment with documentation and maintenance, maintaining full traceability. AKVA Observe uses artificial intelligence to analyse the different data and video streams at the site and advise the operator when it is time to increase or decrease feeding (AKVA group, 2019e).

As the Norwegian fish farm industry is experiencing a technological paradigm shift, and it exists new technology that enable the farmer to achieve better control of the environment, make smarter decisions, increase efficiency in production and a achieve a higher level of safety, it is decided to deliver a control system that can offer all these possibilities to all customers (Alfredsen, 2018).

Module 13 - Power supply and standby generator

When it comes to power supply, a concept with a backup generator is chosen. From the Preliminary Hazard Analysis one could see that the hazardous events with the most critical consequences were related to power shortage, and a standby generator was suggested as a risk reducing measure. When it comes to the concept of the main power source, two alternatives are considered. Either to connect to the powerlines on land or to use a diesel generator placed on the feeding barge. If the power line at the location is dimensioned for it, the customer has access to infinite amounts of electricity and a relatively stabile power source compared to the generator. If the power line is not dimensioned for this type of use, it needs to be upgraded, which is expensive. It is also expensive to lay a sea cable out to the fish farm if it is located far from shore. A dieses aggregate, which is the second option, creates a lot of noise and emissions which may be unpleasant for the workers, bad for the farmed fish and the environment in general. Based on these considerations, worked out in consultation with one employee of THEMA Consulting Group, power obtained from the power lines is the preferred option, if the infrastructure allows for it.

Module 14 - Feeding system

The main function of the feeding system is to feed the fish. Both subsea feeding systems and over water feeding systems are offered on the market. AKVAsmart CCS feed systems has been the worlds best selling feeding system, and is therefore the selected concept. It is designed to fit all feeding regimes, from high to low capacity. It can handle more than 40 feed lines running in parallel, all operated from one PC, iPad or smartphone (AKVA group, 2019b). Due to its flexible field of application, it is decided to deliver this system to all customers.

Module 15 - Lights

When it comes to lightning, LED lights and metal halide lights were considered as possible options. Either of the concepts were considered better than the other, but as standardization of the system is desired, it was decided to include LED lights in all deliveries. By correct use of these, the farmer is promised reduced fish maturation. In addition, lightning leads to faster growth and more effective feed utilization (AKVA group, 2019a). Six LED lights with an effect of 510 W, is installed under water inside each cage.

Module 16 - Dead fish handling

Both a lift up and a dead fish removal basket was considered as possible concepts for dead fish handling. It was decided to deliver a lift up system to all customers. The lift up is placed in the bottom of the net, and has a hose attached to it, leading up to the surface. The dead fish handling system is delivered with a capacity of 500 kg/hour.

Module 17 - Pullert and fender

The pullerts and fenders make it is possible to access the cage by boat. It is offered four of this module, and they are spread around the floating collar. At each of these spots there are four pullerts and six fenders.

Module 18 - Rescue ladder and lifebuoy

This module consists of eight rescue ladders and two lifebuoys, and are suppose to increase the safety for the workers at the fish farm. Each rescue ladder has the capacity of one person. In addition two lifebuoys are installed.

8.3 Information Obtained from Customer

This section presents the information that must be obtained from the customer for each specific delivery. The information is crucial to be able to deliver a system that is customized.

This includes information about the customer's production plan, information from the site survey for the specific location and additional customer wishes. How the input from the production plan and site survey affect the design is to a large extent determined by laws and regulations. It is however not a matter of course that the customer can choose between different options when it comes to treatment of the inlet water, waste collection, depths the inlet water is pumped from and the type of oxygen source. Information about customer wishes is added in order to make the product attractive compared to competing products. The list below presents the information that must be obtained from the customer:

- Production plan
    - ▷ Total volume
- Information obtained from the site survey
    - ▷ Velocity of current
    - ▷ Waves and wind velocity
    - ▷ Effect of ice
    - ▷ Water depth, bottom type and topography
    - ▷ Direction of current, waves and wind
    - ▷ Infrastructure at the location
- Customer wishes
    - ▷ Filter, UV treatment and elfilter
    - ▷ Waste collection
    - ▷ One or two inlets on the riser
    - ▷ Oxygen source

Production plan

Total volume

By obtaining information from the customer's production plan, the necessary total volume of the cage can be calculated. It is crucial to know the total volume as it is one of the parameters having the larges impact on the design of the cage. For instance, the volume determines the needed dimensions on several components. It also affects the necessary capacity of water exchange, oxygen supply and power.

The fish farmers production plan contains information about the amount of fish planned to farm in the cage, the maximum average weight of the fish and the fish density. By implementing this information in Equation 8.3 the total volume can be calculated.

$$Volume = \frac{n_{Fish} \cdot \overline{w}}{\rho_{Fish}} \tag{8.3}$$

For open net pens the maximum allowed density is 25 kg/m^3, but for post-smolt in closed containment systems, fish densities as high as 75 kg/m^3 has been accepted. That is because new knowledge has shown that good fish welfare can be maintained at higher densities in closed containment systems that in traditional cages (Calabrese, 2017). In traditional fish cages, the maximum number of fish in one cage is set to 200 000 individuals (Akvakulturdriftsforskriften, 2008). For closed containment systems, it is possible to apply for an exception from the rule, and today several holds more than 200 000 individuals. Section 4.2 described the production plan for on-growth of post-smolt. It states that the planned maximum weight of the fish usually is between 0.5-1.5 kg.

Information obtained from the site survey

According to NS 9415 the main components of a fish farm must be designed to be able to withstand the loads to which they will be exposed at a site. The main components include the floating collar, mooring system, net pen and feed barge. The site shall be surveyed and described based on topography and degree of exposure in the form of parameters that shall form the basis for calculation of environmental loads on an installation. Measurements shall be performed on empty sites if possible (Standard Norge, 2009). It will now be described how the information in the site survey is obtained. All the information about the site survey is obtained from NS 9415.

Determination of velocity of current

The measurements related to velocity of current shall be taken at a minimum of two levels, 5 meters and 15 meters below sea level if topography allows. They shall be undertaken at the place that is expected to have the highest current velocities at the site and the measurements shall be representative of the area where the fish farm is to be located. Measurements of current velocity entail registration of both time, velocity and direction during the whole of the measurement period. The critical current components contributing to the total current overview shall be assessed and documented, these include:

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

In order to determine current velocity with a specified return period, the multiplication factors of 1.65 and 1.85, for a return period of 10 and 50 years respectively, are used.

Determination of waves and wind velocity

According to the standard, calculation of maximal significant wave height with a return period of 10 and 50 years shall be conducted for all eight orientations. In addition to wind-induced waves and ocean swells, other wave conditions that may occur on the site shall be assessed and documented to see how far they can affect the wave spectrum. These include ship-generated waves, wave reflections, wave trains and wave/current interaction.

Determination of the effects of ice

Danger of icing on marine fish farms shall also be documented. This shall be done on the basis of the following meteorological data for the site:

- Air temperature
- Wind and exposure to wind
- Waves and exposure to waves
- Sea temperature

The danger of drift ice at the site and the danger of the site freezing shall also be assessed and documented.

Description of water depth, bottom type and topography

Bottom topography and type where the bottom attachments are placed and along mooring lines shall be charted. Bottom depth in the relevant area shall also be charted in a grid with the greatest distance of 10 meters x 10 meters between the registered points. Large irregularities, such as large stones, spines, fissures or large objects shall be noted.

There are several types of bottom attachments used in mooring systems, each suitable for different bottom types. Drag anchors are dragged down into the ground and become fixed and are therefore suitable for sand bottom. Bolts can be used to fasten mooring lines to rocks and are therefore used for rock bottom. Piles are suitable for clay bottoms (Kumar and Karnatak, 2014).

Direction of current, waves and wind

Values for current, waves and wind shall be indicated in at least eight concurrent directions.

Infrastructure at the location

The majority of all fish farms are located close to the shore, and closed containment systems for post smolt are no exception. The infrastructure at the site will determine whether the power supply will come from powerlines or generators. If powerlines are not available, either because the infrastructure at the specific location is not developed or if the site is far from the shore, generators will be used.

Customer wishes

The customer can decide whether to include filters, UV treatment and elfilters to the water inlet systems or not. For this reason, module 7, which consists of these components is an optional module. Further, the customer can decide whether the waste that is pumped out of the cage shall be collected or dumped back into the sea. The third choice the customer must make is whether one or two water inlets for the riser is preferable. Finally, the concept for the oxygen source must be selected. The two alternatives are an oxygen tank and an oxygen generator.

8.4 Presenting the Design Tool

In this section, the relationship between the information obtained from the customer and the different design solutions is given. Together with the information about the standardised modules presented in Table 8.1, the table presented in this section, Table 8.3, constitute the selection base for the customized design. This is referred to as a simple tool, that is developed in order to propose a customized design of a closed containment system, based on standardised modules.

A description of the simple tool will now be given. The design is assembled by 18 modules. Eleven of these are standard in all deliveries, while the remaining seven are customized for each delivery, as can be seen from Table 8.3. The table is however only providing information about the modules with more than one design solution. In the column named ”Comment”, the relationship between the suitable design and the information obtained from the customer, is given. Further, the table is built up based on the three available cage volumes. This is because the size of the cage determines the characteristic of several other modules. As already mentioned, the table does not provide details on the part of the design that is standard in all deliveries. This information is provided in Table 8.1.

Table 8.3: Specifications

Component:	**Volume: 9 500 m^3**	**Volume: 12 900 m^3**	**Volume: 15 300 m^3**	**Comment:**
Module 1 - Standard				
Module 2				
Net	Depth: 19 m	Depth: 22 m	Depth: 24 m	
Module 3				
Cloth	Depth: 20 m	Depth: 23 m	Depth: 25 m	
Module 4				
Mooring line	All lengths available	All lengths available	All lengths available	Depends on depth at site
Anchor	Drag anchors, bolts and piles are available	Drag anchors, bolts piles are available	Drag anchors, bolts piles are available	Depends on bottom type: Rock - bolt, Sand - drag anchor, Clay bottom - pile
Module 5				
Seawater inlet pump	Effect: 20 kW	Effect: 25 kW	Effect: 30 kW	
Riser	Available with one, two or three inlets	Available with one, two or three inlets	Available with one, two or three inlets	Concept dependent on customer preference
Module 6 - Standard				
Module 7 - Optional and standard				
Filter	Available	Available	Available	Optional
UV treatment	Available	Available	Available	Optional
Elfilter	Available	Available	Available	Optional
Module 8				
Waste hose	Length: 29 m	Length: 31 m	Length: 33 m	
Waste pipe	Collect waste or dump it in sea	Collect waste or dump it in sea	Collect waste or dump it in sea	Concept dependent on customer preference
Module 9				
Oxygen supply	Number: 6	Number: 7	Number: 8	
Oxygen source	Oxygen tank and oxygen generator available	Oxygen tank and oxygen generator available	Oxygen tank and oxygen generator available	Concept dependent on customer preference
Module 10 - Standard				
Module 11 - Standard				
Module 12 - Standard				
Module 13				
Power supply	Powerline and generator available	Powerline and generator available	Powerline and generator available	Concept dependent on infrastructure at the location. If powerline is available, use powerline.
Module 14 - Standard				
Module 15 - Standard				
Module 16 - Standard				
Module 17 - Standard				
Module 18 - Standard				

Reflections on the developed tool

The result from the modularisation process shows that closed containment systems are possible to modularise. That is because groups of components interact with each other at the same time as the interaction between different modules is relatively low. Some of the revealed strengths and weaknesses of the modular design will now be highlighted. The modular product has the benefit of reduced design time and cost. Among other factors, this is because the design of standardised components only needs to be done once and that certificates for main components like the floating collar are already available. The production efficiency is likely to increase, and the expected risk will decrease as it results in a higher chance of eliminating potential failures. The modularised closed containment system also facilitates exchange possibilities. A revision of NS 9415 is in progress, and it is considered beneficial to allow for the possibility to make changes in the design, if required by new laws and regulations. Loss of market orientation can however be expected, if for example the volumes supplied are not in line with the demand on the market. The weight and structural volume of the product are also expected to be higher than for individual designs, for example as a result of the standardised floating collar.

The design proposed by the tool consists of 18 modules, eleven standardised and seven that are customized for each delivery. As no existing method is able to determine whether a module shall be standard or not, the decision must be based on the designer's knowledge and experience. It is decided to make a module standard if the information given by the customer do not affect its design or its ability to fulfil the function it is meant to. However, one exception is made. If a design is depending on the volume of the cage, there are in some cases found suitable to over dimension the module for the smallest deliveries, instead of supplying different sizes for each volume. An example is the floating collar, where a version designed to provide sufficient buoyancy for the largest volume, is supplied in all deliveries. The same decision is made for the water outlet system, the dead fish handling system and the cameras, among others. Modules that are independent of the information given by the customer, like the control system, the rescue ladder and rescue buoy are also standard in all deliveries. The solution space of the customized modules is with intention kept as small as possible. The downside of delivering a product with relatively few possibilities for variation is that one can lose a market share if the supplied product is not in line with the customers' wishes.

Some of the choices made when establishing the solution space of the different modules were of greater importance than others. One of these is the decision of only offering three cage volumes. This is based on Botngaard System's experience with customers mainly demand cages within this size range. Further, the decision of keeping module 1 standard in all deliveries is of great importance for the final result of the design. An advantage from supplying the same floating collar in all deliveries is that the component is already certified, and both time and money are saved as this do not need to be done for every delivery. A disadvantage from doing this is that the component is oversized for the smallest volumes as it must be designed to provide sufficient buoyancy for the largest construction. This is however not viewed as problematic, because the supplied constructions demand approximately the same buoyancy. This is because the varieties of the weight of the different constructions are not so large, as the size range of the supplied volumes is limited.

A final remark regarding the mooring system will now be given. It turned out to be more challenging to develop a solution space for this module than for the others. A decision of customizing the mooring system for all deliveries was therefore made. This decision is supported by NS 9415, where it is stated that all main components except the mooring system must be product certified. The mooring system shall be designed by a company or a person that is certified, and a customized design must be made for each delivery.

Chapter 9

Case Study

A case study is carried out in order to illustrate the design process for a specific delivery. The design will be customized based on information obtained from a site survey, the customer's production plan and additional customer wishes, presented in Section 8.3.

As the process of selecting a customized design is inspired by Botngaard System's deliveries, it was desirable to perform the case study on another site then they have delivered their products to. Therefore, a site located outside of Frøya in Trøndelag called Rataren, was chosen. It belongs to Salmar Farming AS, SINTEF Ocean AS and Hitramat Farmin AS, (Fiskehelse, 2019). Havbrukstjenesten AS has performed the site survey (Havbrukstjenesten, 2013). Figure 9.1 illustrates the location of the site (Norgeskart, 2017).

Figure 9.1: Location of Rataren outside of Frøya, map scale 1:5000 meters (Norgeskart, 2017).

9.1 Overview of the Project Delivery

Figure 9.2 illustrates the steps of the project delivery for closed containment systems. It is based on information from Botngaard System's previous deliveries. The purpose of this illustration is to give an overview of a typical delivery. Each of the steps of the project delivery will now be described.

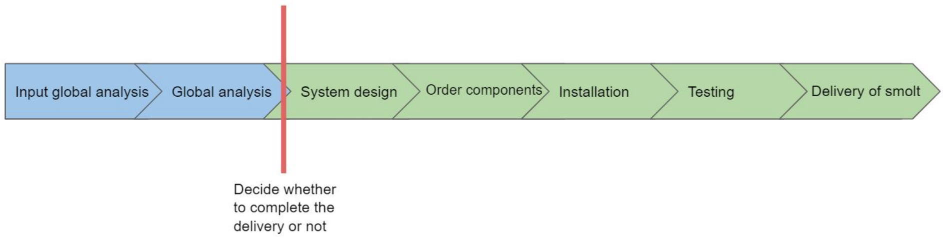


Figure 9.2: Timeline for the project delivery

The first step is to obtain information about the production plan, the site survey and customer wishes. In the next step, this information will be used as input to a local strength analysis, a global strength analysis, a mooring analysis and a fatigue analyses, as described in Section 6.2.1. When the analyzes are performed, a decision has to be made on whether to complete the delivery or not. If it is decided to complete the delivery, the next step, which is the system design, will be carried out. In this step the details of the design will be specified, the location will be inspected and an assessment of the water quality will be done. In addition, further project planning will be carried out. In step four, all required components are ordered and the location is prepared for installation. The lead time of the different components will impact the duration of this step. When a weather window occurs, the installation will take place. In the two final steps of the process, the system is prepared for delivery of smolt. By now, all approvals and certificates should have been approved, and a final test of the system will be performed to check that the equipment function as planned.

9.2 Presenting the Information Obtained from the Customer

In this section, the information obtained from the customer for the specific delivery will be presented. Table 9.1 presents the parameters obtained from the customer's production plan, the site survey, and additional customer wishes. As described above, the information is used as input in the first step of the timeline shown in Figure 9.2.

Table 9.1: Information obtained from the customer for the case study

	Design parameter	Value
Production plan	Total volume	10 400 m^3
Information obtained from the site survey	Maximal current	0.71 m/s
	Significant wave height, Hs	1.9 m
	Effect of ice	Low
	Water depth	24-50 m
	Bottom type	Sand and rocks
	Infrastructure at the location	Powerlines available
Customer wishes	Filter, UV treatment and elfilter	Yes
	Waste collection	Yes
	One or two inlets on the riser	One
	Oxygen source	Oxygen generator

Production plan

The total volume of the cage is 10 400 m^3, calculated as shown in Equation 9.1. The total amount of fish is 400 000, the average maximum weight of the fish is 1.3 kg and the maximum allowed density of fish in the cage is 50 kg/m^3.

$$Volume = \frac{n_{Fish} \cdot \overline{w}}{\rho_{Fish}} = \frac{400000 \cdot 1.3kg}{50kg/m^3} = 10400m^3 \tag{9.1}$$

Information obtained from the site survey

The site survey provides information about waves, currents, the sea floor, infrastructure and the effects of ice at the location. The information related to this will now be presented, and it will be given a short explanation of how it was obtained.

Waves

A combination of wind-generated waves and ocean waves are called combined waves. Figure 9.3 shows that wind coming from southwest and offshore waves coming from west give the highest combined waves. These have a significant wave height of 1.9 meters for a 50 year return period. It will now be given a short explanation of the measurements taken regarding the wind-generated waves and the ocean waves.

Combined Waves							
Wind (10 years/ 50 years)		Offshore waves (10 years / 50 years)			Waves acting on the locality (10 years / 50 years)		
Direction	[m/s]	Direction	Hs [m]	Tp [s]	Hs [m]	Tp [s]	Direction
Southwest	28 / 32	West	13.7 /15.1	15.8 /16.6	1.7 /1.9	3.8 / 4.0	227 /226
West	28 /32	West	13.7 /15.1	15.8 / 16.6	1.5 / 1.7	4.0 / 4.0	249 / 249

Figure 9.3: Characteristics of the combined waves (Havbrukstjenesten, 2013)

In order to obtain data for the wind-generated waves, the wind conditions at the site, shown in Figure 9.4, is used. Wind-generated waves are created by wind transferring energy to the water surface in the direction it blows.

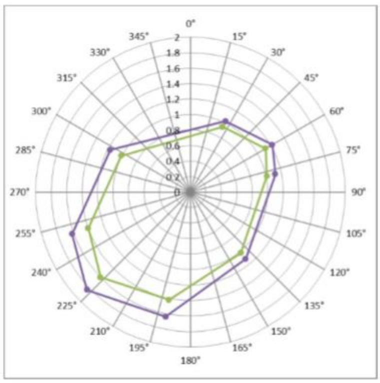
	North	Northeast	East	Southeast	South	Southwest	West	Northwest
Vref	30	30	30	30	30	30	30	30
Vs, 10 yrs	28	25	25	28	32	32	32	32
Vs, 50 yrs	32	28	28	32	35	35	35	35
Vst, 10 yrs	26	23	23	26	28	28	28	28
Vst, 50 yrs	28	25	25	28	32	32	32	32

Figure 9.4: Wind conditions at the site, used to obtain wind-generated waves (Havbrukstjenesten, 2013)

By using a SWAN model the wind-generated waves both for a 10 and 50 year return period, as shown in Figure 9.5, is obtained. Figure 9.5a provides the characteristics of the waves, and Figure 9.5b shows the wave height rose. The largest wind-generated wave for the site has a significant wave height of 1.8 meters and is generated by wind from southwest.

Wind-generated Waves								
	10 years				50 years			
		Waves acting on the locality				Waves acting on the locality		
Wind direction	Wind [m/s]	Hs [m]	Tp [s]	Direction [°]	Wind [m7s]	Hs [m]	Tp [s]	Direction [°]
North	26	0.9	2.9	26	28	1.0	2.9	26
Northwest	23	1.1	4.0	60	25	1.2	4.0	60
East	23	1.0	3.7	78	25	1.1	4.0	78
Southeast	26	1.0	3.5	140	28	1.1	3.7	140
South	28	1.4	4.5	192	32	1.6	4.7	191
Southwest	28	1.6	4.0	227	32	1.8	4.0	227
West	28	1.4	4.0	250	32	1.6	4.2	250
Northwest	28	1.0	2.8	298	32	1.2	2.9	298

(a) Characteristics of the waves



(b) Wave height rose for the waves

Figure 9.5: Wind-generated waves (Havbrukstjenesten, 2013)

In addition to wind-generated waves, the location will be affected by ocean waves. Ocean waves are moving from open sea towards the shore. Several islands are protecting Rataren from the open sea and therefore the site is only affected by small ocean waves. Figure 9.6 shows the characteristics of the ocean waves acting on the location. It can be seen that the largest ocean waves have a significant wave height of 0.4 meters and come from west.

Ocean Waves										
	10 years					50 years				
Offshore	Offshore		Waves acting on the locality			Offshore		Waves acting on the locality		
Direction	Hs [m]	Tp [s]	Hs [m]	Tp [s]	Direction [°]	Hs [m]	Tp [s]	Hs [m]	Tp [s]	Direction [°]
North	11.2	14.3	0.1	14.0	132	12.3	15.0	0.1	14.2	134
Northwest	14.0	16	0.1	15.8	146	15.4	16.8	0.2	16.7	152
West	13.7	15.8	0.3	15.4	165	15.1	16.6	0.4	16.3	169
Southwest	12.4	15.1	0.2	13.2	158	13.7	15.8	0.2	15.4	163

Figure 9.6: Characteristics of the ocean waves (Havbrukstjenesten, 2013)

Current

The tidal current is measured at a depth of 5 and 15 meters. The measurements show that the velocity is highest at 15 meters depth, with a speed of 29 cm/s. Figure 9.7 illustrates the measured current velocities in the different directions at this depth.

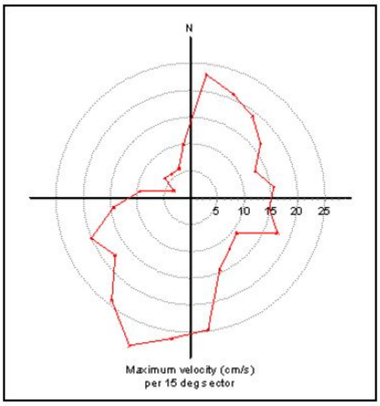
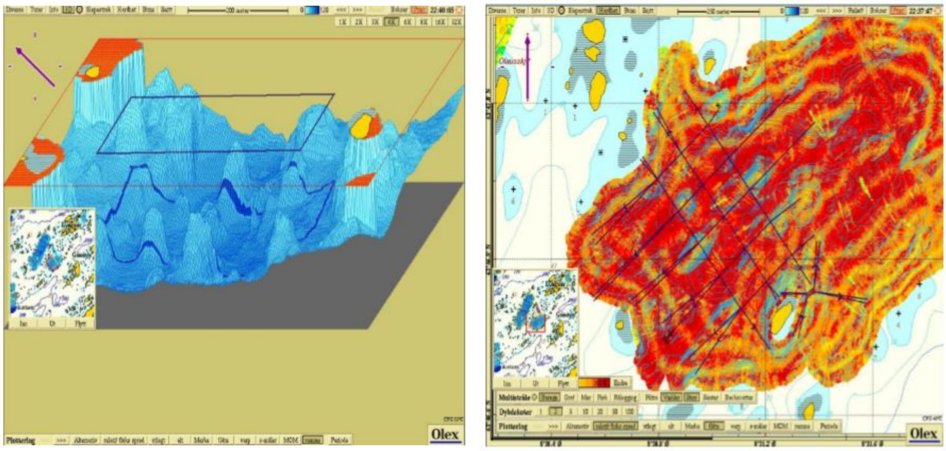


Figure 9.7: Measurements of tidal current velocity in the different directions (Havbrukstjenesten, 2013)

In order to find the total current velocity, a number of season based current contributions must be taken into account. This includes wind-generated current, outbreaks of coastal current and ice melting. The total current velocity, including both the tidal current and the contributions mentioned above, is 38.2 cm/s and comes from northeast. Whit a specific multiplication of 1.65 for a 10 year period and 1.85 for a 50 year period, the maximum current velocity ends up at 63 cm/s and 71 cm/s, respectively. The value for the 50 year return period will be used as the design parameter for current velocity.

Water depth, bottom type and topography

Figure 9.8a illustrates a 3D map of the bottom topography, where the depth at the location varies from 24 to 50 meters. Figure 9.8b illustrates the sediment hardness. The sea floor is both made of sand and rocks. The colours illustrate the relative hardness of the sediment, where red is hard sediment and blue is wet sediment.



(a) 3D map of the bottom topography at Rataren **(b)** Sediment hardness at Rataren

Figure 9.8: Bottom topography and sediment hardness at the location (Havbrukstjenesten, 2013)

Infrastructure at the location

Rataren is located close to shore, and power is available from powerlines.

Effect of ice

The site survey concludes that there is no risk of drift ice on the site and the danger of icing is considered low.

Customer wishes

When it comes to the customer wishes, it is preferred to utilize UV treatment, filters and elfilters for the inlet water, to collect the waste from the cage, to have one water inlet on the riser and to use an oxygen generator as the oxygen source.

9.3 Design Proposal

Based on the information obtained from the customer in the previous chapter, it will be proposed a customized design of a closed containment system for the location Rataren. As described in Chapter 8, some of the modules are standard and some are customized for each delivery. The characteristics for the standard modules are given in Table 8.1 in Section 8.1, and the characteristics for the variable modules are presented in Table 9.2.

The minimum volume required for the cage is 10 400 m^3, so the volume of 12 900 m^3 is selected. The depth of the net and cloth related to this volume is 22 meters and 23 meters, respectively. When it comes to the mooring system, it must be designed by a company or a person that is certified, as a customized design must be made for each delivery. The anchor type selected is determined by the bottom type, and drag anchors and bolts are therefore selected. The effect of the seawater inlet pump is depending on the volume and is hence 25 kW. The riser is designed with one inlet as the customer desired. A filter, UV treatment and elfilter are added to the construction. The length of the waste hose is 31 meters and waste collection is facilitated. The system is equipped with an oxygen generator and seven oxygen supplies. Power is supplied from power lines.

Table 9.2: Design specifications for Rataren

Component:	**Volume: 12 900 m^3**
Module 2	
Net	Depth: 22 m
Module 3	
Cloth	Depth: 23 m
Module 4	
Anchor	Drag anchors and bolts
Module 5	
Seawater inlet pump	Effect: 25 kW
Riser	One inlet
Module 7	
Filter	Yes
UV treatment	Yes
Elfilter	Yes
Module 8	
Waste hose	Length: 31 m
Waste pipe	Collect waste
Module 9	
Oxygen supply	Number: 7
Oxygen source	Oxygen generator
Module 13	
Power supply	From powerline

Carrying out the case study has shown that the developed design tool is able to propose a customized design of the closed containment system based on information obtained from the customer. The tool has good usability in the form of high ease of learning to use the tool and high efficiency of performing the tasks. The detail level of the proposed design is however low, so if the tool should be of any use during the early stages of design, work and improvements are still required.

Chapter 10

Discussion

The overall objective of this thesis is to develop inside knowledge for design of customised closed containment systems, based on standardised modules. To achieve this, a methodology was developed. Strengths and weaknesses of the developed methodology are discussed below.

Through implementing the Preliminary Hazard Analysis, the authors gained additional information, beyond what was obtained through the literature review. The results from the analysis revealed that the most critical hazardous events had consequences such as escape of fish, injury or death of employees, reduced fish welfare and dead fish. These findings are in accordance with the main challenges the industry is facing today. In order for closed containment systems to be a preferable option, they should be designed to overcome these challenges. Further, risk reducing measures related to the hazardous events were mapped. The Preliminary Hazard Analysis revealed that it could be beneficial to facilitate the implementation of additional equipment to the system in the future, for example in a situation where new laws and regulations require changes to the current design. To facilitate for a flexible production, standardised interfaces between the components was found to be of high value.

Further, deeper insight was obtained by creating a list of functions the closed system ought to fulfil. The main goal of mapping these functions was to discover beneficial design solutions. Effort was put in establishing adequate functions. Due to time constraints, there is no guarantee that all relevant functions are covered. A better understanding of the system was obtained, and when examining the functions related to environmental forces, it became evident that the existing knowledge on how closed flexible cages respond to external sea loads is limited.

Based on the obtained knowledge, modules were established. A modified version of House of Quality and the Design Structure Matrix provided a solid starting point. The level of detail of the input of the analyses was selected carefully, as it would affect the result if they were to narrow. The results revealed that closed containment systems are possible to modularise, as groups of components interact with each other, and that the interaction between different modules is relatively low. Thus, the advantages from modularisation can be utilized.

The modularisation process resulted in 18 modules. Depending on how the clustering process in the Design Structure Matrix was carried out and which considerations that were taken into account when modifying the modules, a varying result could have been obtained. Eleven of the modules are standard in all deliveries. Professor Jan Ola Strandhagen informed that no existing method is able to determine whether a module shall be standard or not, hence the decision must be based on the designer's knowledge and experience. It is decided to make a module standard if the information given by the customer don't affect its design or its ability to fulfil the function it is meant to. However, one exception is made. If a design is depending on the volume of the cage, there are in some cases found suitable to over dimension the module for the smallest deliveries, instead of supplying different sizes for each volume. This is done in order to benefit from the advantages of standardisation. An example is the floating collar, where a version designed to provide sufficient buoyancy for the largest volume, is used in all deliveries. The same decision is made for the water outlet system, the dead fish handling system and the cameras, among others. Modules that are independent of the information given by the customer, like the control system, the rescue ladder and rescue buoy are also standard in all deliveries. The solution space of the seven customized modules is with intention kept as small as possible. This is done in order to keep design costs and time as low as possible. The downside of delivering a product with relatively few possibilities for variation is that one can lose a market share if the supplied product is not in line with the customers' wishes.

Modularisation balances the concepts of standardisation and customisation, and drawbacks and advantages from both of these design methods will therefore characterise the product. The modular product has the benefit of reduced design time and cost. Among other factors, it is due to the fact that design of standardised components only need to be done once, and that certificates for main components like the floating collar is already available. As a result of modularisation, the production efficiency is likely to increase, and the expected risk will decrease as it results in a higher chance of eliminating potential failures. The modularised closed containment system also facilitates exchange possibilities. A revision of NS 9415:2009 is in progress, and it is considered beneficial to allow for the possibility to make changes in the design, if required by new laws and regulations. There are however some drawbacks of modularisation such as loss of flexibility as tailored customer solutions are not as easily made as they are with individual design. Further, a loss of market orientation can be expected, if for example the volumes supplied are not in line with the demand on the market. The weight and structural volume of the product is also expected to be higher than for individual designs, for example as a result of a standardised floating collar.

By carrying out the case study it is shown that the developed design tool is able to propose a customised design of the closed containment system based on information obtained from the customer. The detail level of the proposed design is however low, and improvements are still required if the tool should be of any use.

Chapter 11

Conclusion and Further Work

Conclusion

In order to give an answer to the main objective of this thesis, a methodology was established. It is concluded that by carrying out the steps in the methodology, valuable inside knowledge for design of customized closed containment systems is obtained. Two important contributions to inside knowledge will now be highlighted. The preliminary hazard analysis provides information regarding the overall risk picture, and by proposing mitigating measures, it contributes to a safer design. The establishment of functions reveals possible design solution, but also additional information valuable for the development of the design.

Implementation of House of Quality proved to be effective in order to present functions and components. The Design Structure Matrix maps the relationship between the different components in a clear and effective way. The results from the analyzes show that closed containment systems are possible to modularise, as groups of components interact with each other but also that the interaction between different modules is relatively low. The modular product has the benefit of reduced design time and cost. Among other factors, it is beneficial to have the documentation for tenders, project planning and certificates available as the design is done once and for all. The production efficiency is likely to increase, and the expected risk will decrease as it has a higher chance of eliminating failures. The modularised closed containment system also has the benefit of customisation, as it facilitates exchange possibilities. There are however some drawbacks of modularisation such as loss of flexibility, market orientation and increased structural volume and weight. These findings emphasize that the benefits from modularising closed containment systems are in a majority, and it is therefore interesting to look further into these solutions.

As no existing method is able to determine whether a component shall be standard or not, and hence the decision must be based on the designer's knowledge and experiences. The modularisation process resulted in 18 modules. Eleven of these are standard, while the remaining seven are customized for each delivery. Whether the most favourable decisions are made or not, is therefore hard to say.

The configuration of the solution spaces within the different modules has an evident impact on the final result. So does the establishment of relations between the information obtained from the customer and the design solutions. The mooring system is however standing out from the rest. Due to, among other factors, the complexity of calculating the systems natural period of motion, it is not possible to obtain a clear relationship between the forces acting on the construction, the needed layout and the geometry of the mooring. It is therefore concluded that standardisation of this module is not suitable, and a certified company should customize the design for each delivery.

If the simple design tool should be of any use during the early stages of design, work and improvements are still required. The next section summarises suggestions to further work.

Further work

The master thesis' approach for design of customised closed containment systems requires further development in order to be used as a tool for design companies. The following improvements are proposed:

- Implement a 3D-tool that can visualize the proposed design.
- Estimate the time from an order is made until the customised system is installed and ready for operation.
- Implement a calculation tool that can estimate the price of the delivery.
- When the revision of NS 9415:2009 is completed, changes in rules or regulations that affect the design of a closed containment system should be considered.
- Establish detailed interfaces between all modules.
- Implementing the newest sensory and software technology in order to utilize real-time sensory data, as well as developing good decision-making and analysis tools to make use of the increasing amount of information.

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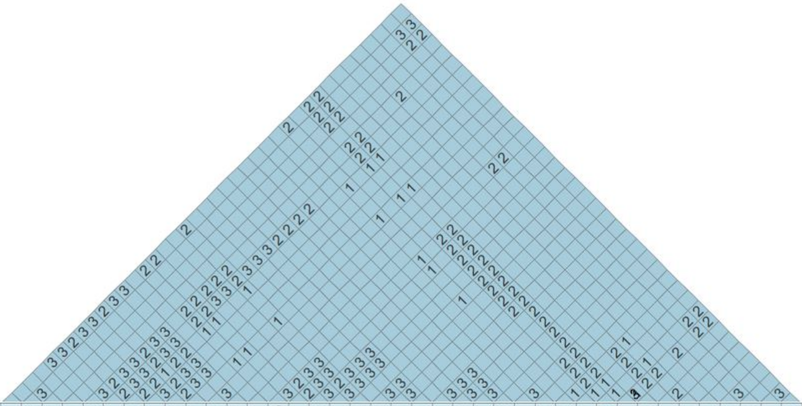
Appendix

11.0.1 House of Quality Diagram



Functions \ Components	Floating collar	Walkway	Handrail	Bird net	Net	Cloth	Splash guard	Mooring lines	Mooring plate	Mooring buoys	Mooring thimbles	Bottom attachment	Marker lights	Seawater inlet pump	Seawater inlet pipe	Seawater inlet grid	Riser	Water outlet system	Filter	UV treatment	Elfilter	Waste pump	Waste hose	Waste collector	Waste pipe	Oxygen supply	Oxygen source	Sensors	Camera	Control system with alarming	Power supply	Standby generator	Feeding system	Lights	Dead fish handling	Pullert	Fender	Rescue ladder	Lifebuoy
Withstand the environmental forces from current and waves	A					A		A	A	P	A	A																											
Having control of the sloshing effects	A				A	A	P	A	A	P	A	A																											
Obtain sufficient buoyancy	A						P			P				P	P			P										P		P	P								
Ensure a barrier between the internal and external environment					A	A								P	P	P	P	P																					
Facilitate for waste handling						P																A	A	A	A						P								
Measure parameters affecting the water quality																												A		P	P								
Maintain favourable values of O2																										A	A			P	P								
Facilitate for beneficial temperatures						P								P			P													P	P								
Provide sufficient water replacement														A	A		A	A												P	P								
Facilitate for beneficial lightning conditions																															P			A					
Facilitate for water treatment and ensure a sufficiently low lice level						A										A	A		A	A	A									P	P								
Maintain a suitable flow pattern					P	P									A															P	P								
Crowding the fish					A																																		
Collect dead fish					P																										P				A				
Possible to access by vessels													P																							A	A		
Safe working space for staff		A	A																											P	P							A	A
Power supply with redundancy																															A	A							
Facilitate for feeding																												P	P	P	P		A	P					

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