Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

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Risk analysis of semi-closed containment systems operating at different exposures.

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
June 2022

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MASTER THESIS IN MARINE TECHNOLOGY

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For stud.techn. Vetle Friis-Vollan

"Risk analysis of semi-closed containment systems operating at different exposures"

Background

Norway is the world's largest producer of Atlantic salmon, and the government has a vision of five folding the production within 2050. However, production has stagnated in recent years due to concerns regarding the industry's impact on the environment and the wild stock. As a result, semi-closed containment systems have arisen as a potential solution to handle these challenges. The technology of producing in semi-closed containment systems is immature, and the risk of using this production method is still unknown. More knowledge and research is necessary to determine the risk of farming salmon in enclosed production volumes.

Objective

This thesis aims to identify hazards and hazardous events when producing salmon in different types of semi-closed containment systems and further investigate how the risks of these hazards and events are affected by operating at sites with different degrees of exposure. The study results will evaluate which structure operates with the lowest risk at different sites.

Tasks

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

a. Discuss Norwegian aquaculture, and challenges faced by the industry.
b. Introduce semi-closed containment systems,
c. Perform a literature review of the different systems, and potential hazards that could affect the risk picture.
d. Present relevant methodology that can be used to analyse the risk in a generic way.
e. Conduct a preliminary hazard analysis for moderate exposure for all types of semi-closed containment systems to identify hazards and hazardous event, and asses the risk.
f. Document relevant approaches and methods for addressing and solving the problem, and choosing an approach/method for one's own work.
g. Carry out a change analysis to evaluate how the risk is affected by moving to more and less exposed areas.
h. Present the results of the risk analysis.

i. Discuss strengths and improvement potential in one's approach and work – with respect to conclusions.
j. Suggestions for further work.

General

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

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

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

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

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

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

Supervision:

Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 11.06.2022

Preface

This master's thesis is the final work of the five years studying Marine Technology at the Norwegian University of Science and Technology. The thesis counts for 30 ETCS , which represents the workload of a whole semester.

I would like to thank my supervisor Bjørn Egil Asbjørnslett at the Department of Marine Technology for his time and guidance throughout the final semester. Further, I would thank my co-students at Marine Technology for good discussions regarding the thesis.

Trondheim, June 10, 2022

Vetle Friis-Vollan

Vetle Friis-Vollan

Summary

Norway is the world's largest producer of Atlantic salmon, and the government has a vision of five folding the production within 2050. However, production has stagnated in recent years due to challenges with sea lice and concerns regarding the industry's impact on the environment and the wild stock. As a result, semi-closed containment systems (S-CCSs) have arisen as potential solutions to manage these challenges. The technology of producing in S-CCS is immature, and the risk of using this production method is still unknown. More knowledge of semi-closed containment systems and how they behave in the sea is required to determine the risk.

In this thesis the risk of producing salmon in three different types of S-CCSs were investigated. The investigation was conducted for flexible, semi-rigid and rigid cages. The hazard identification method, preliminary hazard analysis (PHA), was carried out for all systems operating at sites with moderate wave exposure. The risk found in the PHA for the different systems was compared against each other by using a comparative analysis. Further, a change analysis was conducted for the flexible, semi-rigid and rigid system to investigate how the risk of producing salmon in more and less exposed areas was affected by the changed conditions.

From the risk analysis, it was clear that the flexible system had severe challenges with deformations of the structures when operating at sites with larger waves and stronger currents. Flexible systems also lack the ability to provide protection of critical components such as the water inlet pipe and the dead fish system. The challenges of deformations is less significant for semi-rigid structures, and the structure offers better protection of critical components. A semi-rigid cage will have problems of larger sloshing motions when exposed to larger waves. For the rigid system, the structural ability to provide shelter for critical components within the wall have a risk reducing effect. In addition, the strength of the material eliminates the risk of deformations and makes the rigid system better suited to withstand large forces from the sea or impacts with vessels. However, the rigid structure will have severe challenges with sloshing in more exposed areas.

The results showed that the risk of producing salmon in S-CCSs is acceptable for all types operating in low and moderate exposure, but when operating in moderate exposures risk reducing measures should be proposed. The best structural alternative from a risk point of view, is a rigid system followed by semi-rigid and, at last, flexible. None of the S-CCSs maintains an acceptable risk from a change to high exposure sites. To do so, there is a need for more knowledge and research regarding S-CCSs and the forces acting on the systems.

Sammendrag

Norge er verdens største produsent av atlanterhavslaks, og regjeringen har en visjon om å femdoble produksjonen innen 2050. Produksjon av laks har stagnert de siste årene grunnet store utfordringer med lakselus og bekymringer rundt næringens påvirkning på miljø og villaksen. For å møte disse utfordringene har semi-lukkede oppdrettsanlegg blitt sett til som en potensiell løsning. Den tekniske løsningen i slike systemer er relativt ny og det er lite kunnskap rund bruken av disse som fører til at risikoen ved å bruke denne produksjonsmetoden fortsatt er ukjent. Det kreves mer kunnskap rundt semi-lukkede oppdrettssystemer og deres egenskaper til å motstå krefter fra sjøen for å fastslå risikoen ved bruk av lukket merdteknologi.

I denne oppgaven ble risikoen ved å produsere laks for tre ulike semi-lukkede merdsystemer undersøkt. Undersøkelsen ble gjort for fleksible, halvstive og stive merdsystemer. En fareidentifikasjonsmetode kalt, preliminary hazard analysis (PHA), tok for seg alle de ulike typene systemer som er lokalisert på områder med moderate bølgeeksponering. Risikoen funnet fra PHA for de forskjellige systemene ble sammenlignet med hverandre gjennom en komparativ analyse. Videre ble det gjennomført en endringsanalyse for de fleksible, halvstive og stive semi-lukkede merdsystemene for å undersøke hvordan risikoen blir påvirket og endrer seg ved å produsere laks i slike systemer på både mindre og mer eksponerte områder.

Risikoanalysen viste at det fleksible systemet hadde store utfordringer med deformasjoner av oppdrettsvolumet ved drift på områder med høyere bølger og sterkere strøm. Den fleksible merdens har mindre mulighet til å gi beskyttelse til kritiske komponenter som vanninntaksrør og dødfisksystemer. Utfordringene med deformasjoner er mindre betydelige for halvstive systemer, og konstruksjonen har større mulighet til å gi beskyttelse til kritiske komponenter. Den halvstive semi-lukkede merden vil møte problemer med større skvulpebevegelser inne i tanken når den utsettes for større bølger. For stive systemer vil strukturen i merden åpne for muligheten til å beskytte kritiske komponenter ved å plassere de inne i veggen, skjermet for store krefter fra bølger og strøm, noe som vil ha en risikoreduserende effekt. I tillegg forhindrer det stive materialet strukturen fra å oppleve deformasjoner i strukturen, og samtidig gjøre systemet mer egnet til å tåle store krefter fra bølger, strøm og sammenstøt med fartøy. Konstruksjonen vil imidlertid ha store utfordringer med skvulping inne i merden på mer eksponerte områder. Dette kan skade både strukturen og fisken inni.

Resultatene viste at risikoen som følger ved å produsere laks i semi-lukkede oppdrettsanlegg er akseptabel for alle systemtypene ved drift på lav og moderat eksponering, men at risikoreduserende tiltak bør vurderes ved produksjon i moderate eksponering. Det beste alternativet fra sett med hensyn på risiko, er det stive systemet, etterfulgt av semistive, mens fleksible skårer dårligst i risikoanalysen for alle eksponeringsgrader. Derimot

vil ingen av systemene kunne produsere laks i områder med høy eksponeringsgrad. For å kunne gjøre det er det behov for økt kunnskap og mer forskning om lukket merdteknologi og kreftene som virker på systemene.

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Abbreviations

ALARP = As Low As Reasonably Possible
B = Buoyancy/floaters
Df = Dead fish pump system
DO = Dissolved Oxygen
Fb = Flexible bag
GRP = Glass-Reinforced plastic
HDPE = High-Density Polyethylene
PE = Polyethylene
PHA = Preliminary Hazard Analysis
RPN = Risk Priority Number
S = Structure/wall
S-CCS = Semi-Closed Containment System
TAN = Total Ammonia Nitrogen
UV = Ultra Violet
Wi = Water inlet
Wo = Water outlet

Chapter 1

Introduction

1.1 Background

Norway is the world's largest producer of Atlantic salmon and rainbow trout. After some failed experiments of producing salmon in the 1960s, the industry reached a breakthrough in 1970. Ever since, the industry has grown immensely and is now Norway's second-largest export industry (Regjerningen, 2021). The Norwegian government has stated a vision of five folding the salmon production within 2050 (Regjerningen, 2013). However, over the last years, production has stagnated due to concerns about environmental sustainability when increasing production. The Norwegian government has made the restriction on new production licenses to reduce the impact of the industry on the environment and the wild Atlantic salmon stock (Asche et al., 2019).

There are some significant challenges for traditional net-cage farming concerning sustainability. These challenges are mainly the escapes of farmed salmon, the spread of diseases and parasites, mainly sea lice, and environmental impact due to the release of nutrients, organic matter, and chemicals. To face these challenges and ensure sustainable growth in Norwegian aquaculture, new technologies are required, with some already under testing (Lekang et al., 2016; Fløysand and Jakobsen, 2017; Hersoug, 2015).

In the search for technical solutions to overcome these challenges, several different strategies have been suggested, and some have been developed. A possible solution is to enclose the production volume to separate the farmed fish from the ambient environment by using an impermeable wall. These types of systems are called semi-closed containment systems (S-CCS). The idea is to provide a barrier against sea lice, other parasites, and pathogens in the upper layer of the sea. Also, the physical barrier is believed to eliminate the risk of escapes by using an impermeable material. In addition, it opens the possibility of collecting organic wastes for further utilization and reduces the impact on the local environment. Reusing sludge will open new economic possibilities for utilizing matter described as waste in the past. It will contribute to making modern-day aquaculture more sustainable.

With the planned increase in the production of Atlantic salmon in Norway, there is a need to change production strategies. Moving the production to new sites where the exposure from waves and currents is significantly increased is one. In order to produce salmon in more exposed areas, there is a need for a more substantial and viable smolt. Using S-CCS to produce post-smolt will ensure more robust fish with the ability to grow in such areas without causing injuries or fatigue to the fish.

Another strategy is to shorten the grow-out phase is open net pens in order to increase production efficiency. Increasing the size of the smolt from 200-300 grams to 1-1,5 kg in closed cages will reduce the required area for open net pens and further increase the production per license Henriksen et al. (2012). Shortening the grow-out phase will have a positive impact on aspects like lice and escapes. Less time in open pens means less time exposed to lice and reducing the number of operations that could lead to escapes.

S-CCS can be divided into three main types based on the material and properties of the structure. The three main types of S-CCS shown in Figure 1.1 below are flexible systems, semi-rigid systems, and rigid structures. The flexible structure has negligible bending stiffness and will undergo large deformations when enduring waves and currents. The semi-rigid is less susceptible to more significant deformations under loads. Rigid structures have higher bending stiffness and will not deform under loads. However, for more rigid structures, the mass increases. Concepts are developed for all types and are either producing salmon or in a test phase as pilot systems.

Figure 1.1: AkvaFuture's flexible system(illustration: Akvadesign), Aquafarm's semi-rigid structure Neptune(illustration: Aquafarm) and Dr.tech Olav Olav Olsens rigid cage Salmon Home nr 1(illustration: Olsen (2020)).

Enclosing the production volume sounds like a simple solution to face the challenges in the fish farming industry. However, several new hazards and threats occur for closed containment systems in the sea. Challenges in terms of the construction's response to waves and hydrodynamic properties must be solved before these systems can be implemented on a large scale in the Gorle et al. (2018). To develop reliable structures to reduce the risk of failures and escapes, more knowledge regarding the development of internal waves, called sloshing, is necessary Kristiansen et al. (2018).

The technology is new and immature, whereas the risk is not fully known yet. The existing concepts are designed for low exposure (Iversen et al., 2013). Operating in more exposed areas increases the risk as the system is vulnerable to currents and wave heights Chadwick et al. (2010). For some already operating S-CCS, the results are promising Rosten et al. (2011), but there have been accidents with operating S-CCSs and pilot projects. Unforeseen challenges of wave induced effects and loads have led to damage of the structure, with the potential of salmon escaping (Tsarau, 2017).

1.2 Problem Description

With the desire to increase Norwegian salmon production and reduce the industry's impact on the environment, new technologies have arisen. Floating semi-closed containment systems are proposed to gain production and, at the same time, reduce the impact on the ambient environment. However, new challenges and unforeseen hazards make a threat to both the structures and the fish within.

Fish farming in S-CCS is not used on a large scale, where only a few companies have tested their concepts in sheltered areas with low significant wave heights. Large hydrodynamic forces from waves and currents acting on the structure and critical components have led to a series of accidents and hazardous events.

It is difficult to determine the risk of producing salmon in S-CCSs as there are only a few systems that have operated for a limited time. By enclosing the system, new risks that are non-existent for the traditional net pen arise. Flexible, semi-rigid, and rigid S-CCSs have dissimilar material properties and behave differently in waves and currents. Varying behaviour in the sea, combined with varying material strength, will affect how the risk differs from the structural alternatives. Can one type of cage be more suitable for a specific exposure?

The aim of this master's thesis is to investigate how the risk of operating a S-CCS varies between the structural types. With a focus on the main challenges of escapes, lice, and environmental impacts, in addition to fish welfare and structural damage, does one of the systems ensure a more safe operation? Further, an investigation of how the risk is affected by changing the operation site to more exposed and less exposed areas will be conducted.

Closing the production volume and controlling the water exchange makes the system vulnerable to technical errors. To maintain a safe operation, it is crucial that the main components work appropriately at all times. To assess the risk, potential hazards and threats for the main components must be known, which events that might occur, and what the potential consequences are. The ability to protect critical components mounted on the system varies for the different types of S-CCS.

1.3 Objective

The main goal of the thesis is to investigate the risk of producing salmon in S-CCS and how the choice of structure and site affects the risk. The results of the risk assessment could be used as a guideline for the choice of material and site with the aim of having a low operational risk. An investigation of operating the systems at moderate exposure will be conducted. The risk of operating at moderate exposure will be the reference risk for the different structures. Further, an investigation of how the risk is affected by changing production sites to more exposed and less exposed sites will be carried out. To gain knowledge and determine the risk, the following objectives will be conducted:

1. Gain knowledge of semi-closed containment system and main components of the system from a literature study. Present the different types of S-CCS, and how structural design for flexible, semi-rigid and rigid structures affect the properties and behaviour in sea.
2. Perform a hazard identification for all three structures at moderate exposure to determine the risk of potential hazards and hazardous events for each structural type.
3. Compare the risk for the different structures operating in moderate exposure by conducting a comparative analysis.
4. Investigate how the frequency and consequence of hazardous events is affected by changing operating site to more exposed and less exposed locations.
5. Present the results of the risk analysis, and discuss how suitable the S-CCS are for the different degree of exposure from a risk perspective.

1.4 Scope and Limitation

There are several different designs for S-CCS. Some are already built, and some are still in a concept or model phase. The different designs could have an open rooftop, enclosed rooftop, submersible and semi-submersible cages, rebuilt ships, and raceways. The designs used in the risk analysis for this master's thesis are single floating structures with a free surface and an open rooftop. These types of structures are most used for the existing S-CCS and are, therefore, the investigated structures for this thesis.

The technology is relatively immature and has not been commercially used on a large scale yet. Most of the built S-CCS are prototypes or in test phases. As a result, there is a lack of historical accident data. Hence, estimates of the frequency and severity of outcomes are assumptions and expert opinions from the author based on knowledge gained from the literature review and previous accident events.

The combination of frequency and severity will not be accurate estimates for all hazardous events. However, the risk analysis will highlight relevant hazards and hazardous events, potential risk-reducing measures, and present how risk analysis can be used to identify hazards and determine risks when producing in S-CCS.

Chapter 2

Literature review

Floating semi-closed containment systems(S-CCS) in Norwegian aquaculture is a relatively new and not much-used method used today for salmon and trout production. However, the interest in using S-CCS as a part of the production cycle has grown in recent years. S-CCS has developed rapidly in recent years and is thought to be an alternative to the production of salmon in the sea. In Norwegian aquaculture today, S-CCS are mostly designed to produce post-smolt up to 1 - 1.5 kg, which will result in more resistant and viable fish when put in open-net pens for the growth phase. It will also reduce the production period in net pens from 16-22 months to 10-12 months (Fløysand and Jakobsen (2017);Calabrese (2017)). Dissimilar to the traditional open net pens, a S-CCS will provide a physical barrier to prevent interaction with parasites and salmon escapes in addition to collecting sludge (Espmark et al., 2020). Enclosing the system will remove the natural water exchange that currents provide for open net pens. To provide good water quality inside the cage, large amounts of water from depths where there are no lice, are pumped into the cage and used once before leaving through water outlets. If necessary, oxygen is added to maintain a sufficient dissolved oxygen level.

2.1 Classification

The Norwegian salmon industry is facing several challenges using traditional net-pen technology. The spread of sea lice and parasites between the wild stock and the farmed salmon, escapes from fish farms, and the environmental effect of the release of nutrients and sludge are the main challenges of traditional fish farming (Grefsrud et al., 2019). A proposed solution to face these challenges is semi-closed containment systems in the sea. The purpose of enclosing the system is to prevent interaction with wild species and parasites, reduce the risk of escapes and reduce emissions of organic matter to the local seabed (Rosten et al., 2013). A closed system will have a high building cost and operational cost compared to a traditional net cage. However, if a S-CCS is operating as intended, this could eliminate the cost of delousing and lice handling. The cost of lice handling in Norwegian aquaculture is approximately 5 billion NOK annually (Iversen et al., 2017).

There are different S-CCS types depending on the material and property of the structure. A S-CCS is either a flexible, semi-rigid(semi-flexible), or rigid structure (Strand and Faltinsen, 2020) depending on the bending stiffness of the structure. The different types of S-CCSs will be further described later. With a closed cage, the behavior of the structure will be different from the traditional net pen. Waves will form inside the S-CCS when the system is exposed to waves. Significant waves will develop inside a rigid structure compared to a flexible structure. However, a more flexible cage will deform due to the hydrodynamic forces. To mitigate internal waves, also called sloshing, the eigenperiod of the structure must be known (Snøfulg, 2018) since sloshing is a resonance problem. The most common material used for the different concepts is shown in Table 2.1 below.

Type	**Material**
Flexible	-Fiber-reinforced cloth -Tarpaulin
Semi-rigid	-Glass-reinforced plastic -Polyethylene
Rigid	-Steel -Concrete

Table 2.1: Types of semi-closed containment systems and typical materials for the different types

Henriksen et al. (2012) have proposed a classification of semi-closed containment systems based on the complexity of the system. There are four categories where category I, is the least complex system, and category IV is the most complex, as shown in Table 2.2. Category I is a relatively simple system where an impermeable material encloses the production volume, and the water flow comes from the control of the water inlet and water outlet. Category II has the same components as category I, but implements filtration to remove lice, larvae, and sludge from the water inlet and outlet system. Category III has the same attributes as category II, but eliminates the risk of fish pathogens entering the production volume by use of UV filtration. Category IV is not relevant for this thesis as it refers more to land-based Recirculating Aquaculture Systems(RAS). For every category upgrade, the system requires more equipment, technology, and complexity. More technological equipment implemented in the design will enable better control of the production and water quality. Nevertheless, with more equipment to rely on, they must work adequately at all times.

Category I	**Category II**	**Category III**	**Category IV**
Volume enclosed with a solid wall or cloth	Same as for Category I in addition to:	Same as for Category II in addition to:	Same as for Category III in addition to:
Control of water intake	Double security against escapes	Removal of fish pathogens from water intake (ex: UV-radiation)	Biological water treatment to minimize use of water, and to remove larger amounts of organic waste, nitrogen and phosphorus Possible systems: -Recirculating Aquaculture Systems(RAS) -Solutions with the use of organisms to increase cleaning effect for organic waste and nutrition
Control of water outlet	Removal of lice an larvae from water intake and outlet by use of filtration		
	Filtration of sludge from water outlet		

Table 2.2: Proposed classification of closed and semi-closed containment systems(Henriksen et al., 2012)

To receive development licenses for S-CCS in Norway - a set of demands must be fulfilled. These demands were presented at the aquaculture fair Aqua Nor (Furuset, 2021), and the criteria are

- Zero discharge of lice and lice-eggs
- Minimum 60% of the produced sludge must be collected
- Safety regarding escapes

Based on the demands set by the Norwegian government, some of the categories mentioned above do not provide sufficient control to secure a development license. In the proposed classification from Henriksen et al. (2012) in Table 2.2, it is clear to say that category II is a minimum. Double security against escapes, removal of lice and larvae from the water inlets and outlets, and collection of sludge will help meet the requirements set by the Norwegian government. Category II S-CCSs are the main focus of this thesis, with comments on how implementing UV radiation in the water inlet will have a risk-reducing effect on operating S-CCSs in the sea. The risks of operating different types of S-CCSs with a category II complexity are being investigated further. The goal is to find and evaluate the risk picture for the different concepts based on the degree of exposure. This risk evaluation could be used as a guideline for choosing material and type for a S-CCS for a given site. The system included in the thesis is presented in Table 2.3.

Wave exposure\Type of S-CCS	**Flexible**	**Semi-rigid**	**Rigid**
Low exposure (Hs <1m)			
Moderate exposure (1m <Hs <2m)			
High exposure (2m <Hs <3m)			

Table 2.3: Presentation of the S-CCS and exposures that will be investigated further.

2.2 Technology

For traditional net pens, the environment provides a natural water exchange from currents and other wave-generated movements (Clarke et al., 2018). Necessary oxygen saturation, water temperature, and removes metabolic waste and CO2. The technology behind semi-closed containment systems enables these obligatory processes to happen with pumping systems to maintain sufficient water flow and obtain water quality. Continuously water exchange will provide the fish with oxygen as well as remove the waste from feed and fish for further treatment to keep a healthy environment inside the cage. The internal water is continuously monitored to ensure that concentration of oxygen, CO2, PH, nitrogen, ammonia, and ammonium are within acceptable values.

2.2.1 Water exchange

When enclosing a salmon farm, water quality and control is essential to succeed. Water quality is, to a large extent, influenced by metabolites produced by the salmon. The metabolites that affect fish welfare, growth, and environment mostly are carbon dioxide (CO2) and nitrogen compounds which are formed continuously by the fish metabolism (Terjesen et al., 2003). A high water exchange rate is crucial to mitigate the concentration of CO2 and nitrogen compounds.

A high water exchange rate is essential to maintain an acceptable level of dissolved oxygen(DO). Lack of DO could result in sub-optimal growth conditions, reduced performance, stress, and hypoxia for the salmon inside the cage. The worst case is that it might lead to diseases that can be fatal. The suggested minimum amount of DO is above six mg/L for closed containment farming (Chadwick et al., 2010). In order to optimize water exchange, it is necessary to be able to adjust the water inlet and water outlet.

2.2.2 Water inlet

The S-CCS that operates in Norway today uses flow-through systems. Water is pumped into the cage from a depth where free-swimming lice, larvae, and eggs do not appear (Nilsen et al., 2017). Also, the temperature at these depths is more stable compared to the temperature closer to the surface. Temperature is essential when producing salmon for the fish to perform as intended. The degree of oxygen saturation varies based on salinity and temperature. Oxygen demands from fish also vary with temperature, biomass, and activity (Berget, 2016). S-CCS will enable a more stable temperature throughout the seasons. Moreover, the oxygen demands could be more predictable in S-CCS.

Previous experiments show that sea lice(*Lepeoptheirus salmonis and Cakigus ekingatus*) disperse in the upper layer of the sea, close to the water surface. A model study indicates that the safe water intake depth varies between seasons. During summer, a safe depth could be below 10 m and below 15-20 m during winter. A water intake of 20 m for both seasons is considered a safe (Nilsen et al., 2017).

Water flow inside the cage is vital for the self-cleaning processes to work correctly. Optimizing internal currents will benefit the quality of the salmon and potentially increase the growth rate (Karlsen, 2016). Water pumped up from the deep enters the systems using pumps that make a horizontal circular current for the fish to swim in.

2.2.3 Water outlet

Removing already used water from the system is crucial for maintaining a healthy environment for salmon to grow in. The water outlet transfers water with low oxygen levels out of the system. The location of water outlets is essential concerning the internal currents and waste removal (Klebert et al., 2018). There are several different arrangements of water outlets for the different semi-closed containment systems. Agrimarine and Neptune use adjustable outlets to control the water flow out of the system (Clarke et al., 2018). Adequate water exchange will prevent the formation of carbon dioxide(CO2), leading to stress and a sub-optimal environment for salmon to stay healthy and prevent diseases. In addition, to maintain a healthy environment using water-flow control, control of water outlets has other critical production tasks. An overpressure inside the S-CCS is necessary for a flexible cage to maintain its shape. A pressure drop will lead to the deformation of a flexible material due to the hydrostatic and hydrodynamic forces acting on the structure (Lader et al., 2015). A deformation could affect internal currents, space for fish to move, and the self-cleaning ability of the system.

2.2.4 Oxygen supply

The oxygen requirements are relatively high, with a fish density of up to 80 kg/m^3, close to three times the limit in open cage systems. The usage of oxygen varies with the weight, density, current, and feed ratio (Terjesen et al., 2003), but a minimum of 6 mg/L is suggested for SCCS. Maintaining the minimum DO concentration will require flow rates that could be difficult or practically unattainable to achieve (Boulet et al., 2011). Therefore the supply of oxygen is necessary. To ensure sufficient oxygen levels, oxygen tanks are often mounted to the S-CCSs to increase the amount of dissolved oxygen(DO) and ensure good water quality and fish welfare inside the closed cage. The oxygen is supplied automatically when the sensor systems discover low values of saturated oxygen.

2.2.5 Floating collar and buoyancy

Flexible and semi-rigid structures do not provide much buoyancy from the structure itself. They rely upon buoyancy from floating collars. In addition to the weight of the structure, the floater must carry the weight of increased hydrostatic head (Clarke et al., 2018). Additional weight from dead fish and fouling on the structure must be considered. Rigid cages gain buoyancy from buoyancy chambers located inside the wall of S-CCS (Clarke et al., 2018). The weight of dead fish and fouling is relatively low for a rigid S-CCS since the mass is much higher in comparison to flexible and semi-rigid S-CSSs.

2.2.6 Monitoring and sensor systems

For the fish to thrive and grow as intended in enclosed fish cages, water quality must be obtained. From feed consumption and metabolism, the fish produces waste that mainly contains CO2, nitrogen compounds, and feces, which will affect the fish's welfare, even in small amounts. Monitoring of gasses and particles must be made to ensure that the water provides a healthy environment for the fish. The center of the cage contains the highest concentration of CO2 (Bjerkås, 2018). Hence, the monitoring systems should be mounted close to the center.

The system requires an overpressure to ensure sufficient water exchange and for flexible structures to obtain a fully inflated shape. The water level is higher inside the cage, giving an extra weight inside the cage, which is necessary to push water out of the system (Nilsen et al., 2017). The internal wave height must be monitored to maintain sufficient water exchange constantly.

The production method of closed cages is very sensitive to system failures. Water quality is monitored continuously through a series of sensors and regular testing for DO, PH, temperature, nitrates, nitrites, ammonia, and pathogens to ensure optimal conditions for fish to live and grow in (Leow and Tan, 2020). However, critical system components must be continuously monitored to ensure a quick reaction if failures happen. A technical error in one of the system's main parts is critical and can lead to stress and injuries to the fish, reduced growth, and mass mortality in the worst case.

2.2.7 Dead fish pump and sludge handling

Dead fish, sediments from fish feces, and left-over feed sink to the bottom of the cage. The shape of bottom part of a S-CCS is built for the purpose of collecting the sediments and dead fish. The wastes are transported out of the system through separate tubes from the outlet up to the surface for further processing (Nilsen et al., 2017). Removing waste products is needed to maintain fish welfare. A reduced waste treatment could result in accumulated waste products such as CO2 and ammonia, with a following reduction of pH and higher concentration of metal toxicity (Nilsen et al., 2017).

2.3 Types of S-CCS structures

2.3.1 Flexible S-CCS

Floating flexible semi-closed containment systems are production system that consists of many components where each component has an important function. What separates a flexible S-CCS from semi-rigid and rigid structures is that the material that encloses the production volume will deform under hydrodynamic loads (Strand et al., 2014).

Akvadesign have made a flexible S-CCS that produces salmon. The design of the S-CCS is shown in Figure 2.1. The system stays afloat by use of a floating collar made of concrete. A flexible bag made of tarpaulin is attached to the floating collar. Water pumps mounted to the top of the floating collar inserts water taken from depths of 25 meters that enters the system in a horizontal circular current. At the bottom of the bag, a combined water outlet and waste handling system release used water and remove sludge and dead fish from the production volume. Dead fish and sludge are pumped to the surface for the filtration of the sludge and dead fish. In addition, there are several sensors and monitoring systems continuously operating at the farm. These systems control oxygen supply, filling level, stability of the floating structure, and several other features. As a safety measure from escapes, a safety net is mounted outside of the closed wall in case of a rift in the tarpaulin occurs.

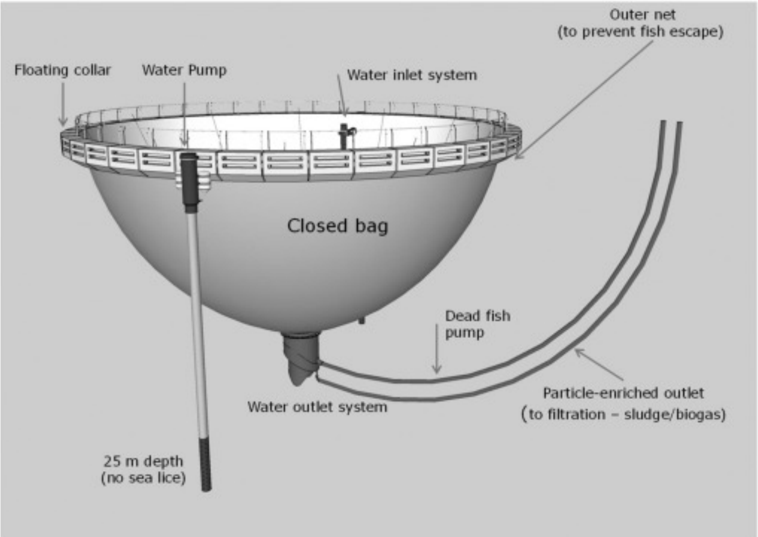


Figure 2.1: A design of a floating semi-closed containment system made of flexible tarpaulin. (Illustration: Akvadesign)

A flexible structure does probably have a lower cost compared to semi-rigid and rigid structures (Clarke et al., 2018). However, with flexible material, a different risk picture will occur. Deformation from static and hydrodynamic forces could arise. The filling level of the bag is a critical aspect to evaluate as well as the exposure of such loads. If the filling level is reduced, the ability of the bag to deform arise(Strand et al., 2014), and drag forces will increase due to a parachute type of formation. An experiment performed by Lader et al. (2015) showed that drag forces on a deflated bag were up to 2,5 times the drag forces of an inflated bag. In recent years NS-9415 (2021) has set demand for higher internal water lines compared to the outer water line for flexible cages.

The internal excess pressure will cause a discharge of contained water if a rift or hole in the bag occurs. Discharge may lead to draining of the bag structure, which can be critical for closed flexible cages (Kristiansen et al., 2018). This would reduce the production volume and cause a higher fish density. With higher density, there could be lower oxygen levels and increased concentration of CO2, particles, and NH3. In the worst case, fish could be crushed, or it may cause escapes if the hole is big enough. Therefore, the strength of the material is crucial to withstand these forces. Also, a safety net outside of the closed bag will ensure double safety regarding escapes.

Snap loads are a concern that is special for flexible materials. If the dynamic tension works in the same order as the static tension, there could arise a zero tension of the material with the following snap load (Strand, 2018). The prediction and calculation of the hydrodynamic forces are complex because of the closed flexible material. Knowledge of these structures is limited, and sufficient simulation programs are yet to be made for these types of calculations. Open systems and rigid systems have sufficient knowledge from years of developments in fish farming and the petroleum industry.

Deformations in the structure will affect several aspects of the system. Drag forces will increase if deformations occur and the structure loses its circular or cylindrical form. Demands for a more robust mooring system are needed. Deformation may also affect the internal water flow, where the self-cleaning ability may be mitigated, and the accumulation of organic matter in the form of feed and feces could occur. Deformation and motion close to the dead fish pump might cause a hazard of tearing. Such deformations and motions close to the dead fish pump system could increase the risk of escapes due to damage to the tarpaulin. The water outlet and the dead fish pipelines were covered by a standard fish net (Nilsen et al., 2017)

Flexible S-CCS using fabric as the structure will probably end up as the least expensive alternative for S-CCS (Clarke et al., 2018). This has made the fabric structured containment system design a popular choice for early experimental programs, with Ecomerden, Botngaard, and AkvaFuture using this design strategy. The systems' volume and their upper limit of significant wave heights are listed in Table 2.4.

S-CCS	Material	Volume [m^3]	Significant wave height [Hs]
AkvaDesign	Polyester	5 560	1,2 m
Ecomerden	Strong flexible fabric	3 500 and 29 000	2,5 m
Botngaard System	Fabric composite	2 500 and 8000	2 m

Table 2.4: Design information of flexible S-CCSs.

2.3.2 Semi-rigid

Semi-rigid S-CCS is a used concept in Norwegian aquaculture. A semi-rigid system has higher stiffness than a flexible cage but will experience severe deformations from static and dynamic forces from waves and currents (Su et al., 2019). Existing systems are mostly made of GRP or PE. The material's stiffness increasingly allows internal waves to develop inside the cage since the damping due to deformation is reduced, as sloshing motions are more significant for more rigid structures (Sintef, 2018). If waves are generated inside the cage and evolve, this will cause stress and loads acting on the structure. Over time internal waves, also called sloshing, might cause damage to the material. To avoid severe sloshing motions within the semi-rigid cage, the structure's design must be evaluated carefully.

The components needed to operate in a semi-rigid cage are similar to a flexible S-CCS, but the structural difference includes some operational changes. Since the material does not deform as much, there have to be implemented other operational systems for collecting fish. These could be an internal collector that leads fish toward the surface or bilge systems that elevate the whole structure by pumping out water inside the containment.

Figure 2.2: Aquafarm´s concept Neptun (illustration: Aquafarm)

In Figure 2.2, an illustration of Aquafarm´s concept Neptun is shown. Aquafarm states that the structure is made of GRP, with some steel reinforcements on the areas that endure the most stress. Pipes for water inlets are adjustable and extract water from depths of 25 meters or more. The extracted water is treated with UV radiation above sea level before entering the system in a circular flow. Water treatment above the surface allows for easier maintenance and repairs. The water outlet is located at the bottom of the cylinder with filtration systems that prevent waste from fish and feed from being released to the outer environment. Sludge and dead fish are collected at the bottom and transported to shore. The S-CCS is designed for strong winds of up to 30 m/s, currents of 1 m/s, and a significant wave height of 2 m.

A semi-rigid system does not have the same ability to protect critical components as rigid structures. Water inlet pipes, water outlets, and dead fish pumps are mostly located on the outside of the cage, exposed to massive forces from waves and currents, as seen in Figure 2.2. Some semi-rigid systems are already made and operate at sites with significant wave heights up to 2,5 meters. The systems are presented in Table 2.5.

S-CCS	Material	Volume [m^3]	Significant wave height [Hs]
Aquafarm Neptun	Glass-reinforced plastic with steel reinforcement	21 000	2 m
Fish Globe	Reinforced polyethylene	3 500 and 29 000	2,5 m

Table 2.5: Existing semi-rigid systems, the material of the structure and significant wave height they are designed for.

As seen in Table 2.5, the Fish Globe have produced two S-CCSs. The cage with the lowest volume is for producing post-smolt before the fish are put to open pens in the sea. The most prominent structure can produce salmon up to slaughtering.

2.3.3 Rigid

A closed cage with a rigid material is built to withstand larger loads. For rigid structures, there is no doubt that the material offers a more reliable construction to withstand forces from more extreme currents, wind, and wave conditions than other systems with more flexible materials (Clarke et al., 2018). The technology behind a rigid S-CCS is often based on knowledge from the petroleum industry. Typical materials for these structures are concrete and steel. The structure is robust, and the structure's mass is large compared to flexible and semi-rigid bodies. Production costs will increase due to higher material costs, i.e., building costs and installation costs.

A rigid structure will not experience deformations when exposed to large forces from waves and currents. The material is less fragile than the other alternatives, making it more reliable concerning structural damage due to impacts between operating vessels and the S-CCS. Further, the structure enables the possibility of protecting critical components from sea loads by locating them within the flotation chambers inside the wall. Water inlet pipes, dead fish pipes, and water outlets are sheltered from hazards that could cause damage. However, here are some concerns surrounding semi-rigid and rigid closed containment systems. From an engineering point of view, these concerns are based on whether solid walls can withstand forces from the currents and waves over time (Chadwick et al., 2010).

A rigid body in waves will result in large masses put in motion. The incoming waves could excite the free surface of the water within the system. Experiments show that rigid structures experience more significant sloshing motions than the other S-CCSs (Sintef, 2018). Internal waves might be of such severity that it causes damage to the structure and reduces the structural integrity. Sloshing will also be found to have a significant effect on the coupled surge and pitch motion of the structure (Su et al., 2021). The system must be designed to avoid resonance, where the eigenperiod of the system is crucial. A mooring system requires more strength as larger masses are put in motion, and increased forces are acting on the mooring components.

Figure 2.3: Dr.Tech Olav Olsen's rigid S-CCS Salmon Home No 1 (illustration: Olsen (2020))

There are few concepts of rigid structures made of concrete or steel, but Salmon Home No 1, seen in Figure 2.3 is one. The water inlets are protected in voids inside the impenetrable wall, and the dead fish pump and pipe are mounted on the inside. As a result, the components are sheltered and protected from external forces. The system is a pilot project built for significant wave heights of 0,8 m.

2.4 Accidents when producing in semi-closed containment systems

Production of salmon in floating semi-closed containment systems is relatively new and has not been tried much yet. However, there have been experienced some accidents and hazardous events for the companies that have started using this production method. There are many varying causes of accidents, and the outcomes are many. Some have experienced structural damage due to rough weather and hydrodynamic loads exceeding what the structures were designed for. Technical problems have been an issue, as the production method is very sensitive to technical failures. Others have experienced unwanted pathogens and organisms entering the cage, either from entering from the water inlet pipes or over the floaters directly into the production volume. Some of the hazardous events and accidents will be further described.

2.4.1 Structural damage

During the short time of using S-CCS as a production strategy, there have been accidents where systems have lost structural integrity. Damages caused by extreme weather or rough sea resulted in system components breaking and cracks in the structure. Companies like Cermaq, AgriMarine, and Ecomerden have all experienced damage to their systems as a result of forces acting on the structure.

Røen (2014) published an article informing that structural damage occurred for Aquadome during the test phase located at Vestlandet in Norway in autumn 2013. A storm caused large loads on the system leading to one of the water inlet pipes breaking; as a result water inlet was reduced from 18 meters to only 2 meters, where the density of lice was higher. Lice infested the fish inside the production volume.

Another containment system that encountered large forces during a storm was AgriMarine's S-CCS called Tank 1. During a winter storm in 2011, the concrete structure was exposed to considerable stresses, eventually developing a crack in the wall where 2745 Chinook salmon reportedly escaped through(Grydeland, 2012).

During the first batch of salmon in Ecomerden, cracks developed in the water inlet pipes causing lice to enter the system(Berge, 2017). The cracks caused water from eight meters containing lice to enter the system, but there were no significant lice problems. The damage is assumed to be location dependent as the forces acting on the pipes might be too large at the respective location.

Aquafarm Equipment's closed cage was damaged when a storm called Nina arose in January 2015. The semi-rigid system containing halibut took damage from the storm, with cracks developed on some of the outer flanges on the walkways. The system had to be transported onshore for repairs(Grindheim, 2015).

2.4.2 Technical error

In addition to the water inlet pipe damage on Aquadome, Røen (2014) informed that there had been experiencing some technical failures in the water inlet system, causing an oxygen drop where 25% of the fish died. The rest had a low growth rate.

A technical failure caused several stops in AkvaFuture's flexible production system. Water inlet pumps stopped working, and artificial lights went off, causing stress for the fish resulting in several hundred fish escaping through the water inlet pipes(Budalen and Rørstad, 2013).

Cermaq Canada tried producing salmon in one of their systems in Vancouver on the west coast of Canada in autumn 2020. During the third out of four phases, the system had technical errors causing the water quality to drop. The water conditions became too poor for production, and the remaining healthy fish had to be slaughtered(Wilcox, 2021).

2.4.3 Organisms and pathogens entering the system

In May 2016, during a pilot production of post-smolt, Ecomerden had immense challenges with jellyfish entering the production system(Furuseth, 2016). Suddenly the appetite for the salmon stopped, and the fish's health got worse over time. It became a significant problem at the beginning of June 2016 when 4 000 - 5 000 fish died daily. The tank originally containing 89 000 post-smolt of 1,1 kg had to be emergency slaughtered. In the end 20, 000 fish died before slaughtering.

Chapter 3

Methodology

This chapter will present the methods used for this master thesis. Floating semi-closed containment systems are relatively new technologies and are not much used in Norwegian aquaculture yet. Therefore it is not sufficient data to fully understand the risk of implementing S-CCS in the industry (Grefsrud et al., 2021).

To identify and understand hazard and threats for the different S-CCSs, hazard identification methods was used. Rausand and Haugen (2020) defines hazard identification as the process of identifying and describing all the significant hazards, threats, and hazardous events associated with a system. There are several methods for hazard identification. For this thesis, the method of Preliminary Hazard Analysis(PHA) was used for each of the systems for the different sea exposures. PHA is a suitable method as it is intended for covering hazards and accidents in an early stage of the design phase. In addition, a PHA will provide a ranking for the hazards and the hazardous events based on a Risk Priority Number(RPN) which is beneficial for comparing the risk picture for rigid, semi-rigid, and flexible structures.

A comparative analysis was conducted using the Risk Priority Numbers(RPN) from the PHA. The comparative analysis assesses how the risk varies for the system elements of the different S-CCS. The analysis provides a scoring system that ranks flexible, semi-rigid, and rigid systems from the safest to the least safe for a given degree of exposure.

Further, a change analysis was used to investigate risk changes when systems are moved to other locations with either higher or lower degrees of exposure. The change analysis is built on the PHA, where estimating a new risk for the hazardous events and possible outcomes due to the change of location is the goal.

3.1 Preliminary Hazard analysis

To identify possible hazards and accidents in an early stage of the system design, a preliminary hazard analysis is a suitable method(Rausand and Haugen, 2020). PHA does not necessarily require a detailed design of the system to be complete but opens for the identification of possible hazards at an early stage of the design process and thus assists in the choice of the most advantageous arrangement of facilities and equipment(Vinnem and Røed, 2020). Identifying hazards and ranking them based on the frequency of occurrence and consequence makes it easier to compare the risk for different types of S-CCS. The objective of this master's thesis is to understand and evaluate the risk for the different types of systems based on the degree of exposure. Based on the risk analysis, proposed design strategies can be made to reduce the risk of accidents when operating a S-CCS at a given location. Conducting a preliminary hazard analysis will give a solid foundation for supporting the proposed strategy.

To approach the PHA process, a series of steps suggested by Rausand and Haugen (2020) have been performed. The method is an analysis procedure that consists of seven steps that will be further described. The process is shown in Figure 3.1 below. The series of steps are

- Step 1: Plan and prepare
- Step 2: Identify hazards and hazardous events
- Step 3: Determine the frequency of hazardous events
- Step 4: Determine the consequence of hazardous events
- Step 5: Suggest risk reducing measures
- Step 6: Assess the risk
- Step 7: Report the analysis

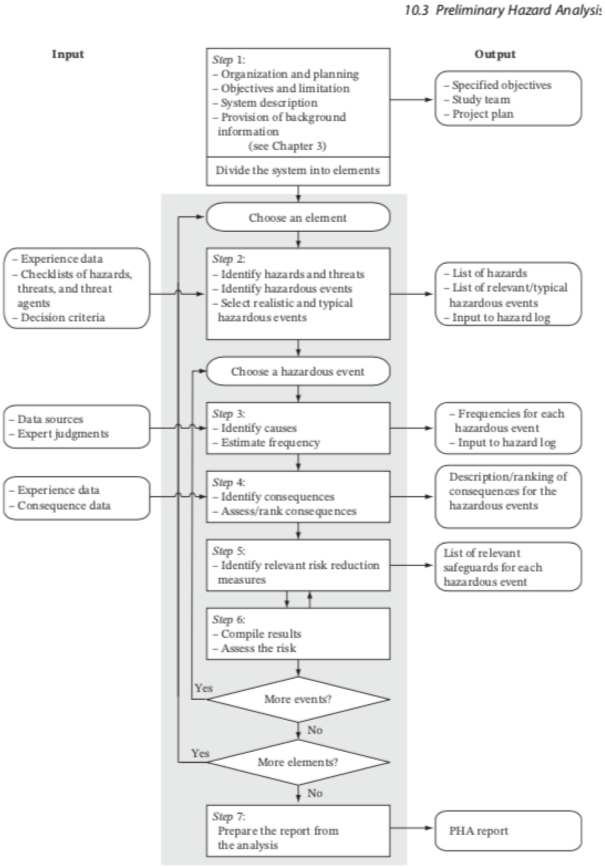


Figure 3.1: Preliminary hazard analysis procedure. Source: Rausand and Haugen (2020).

3.1.1 Step 1: Plan and prepare

The primary purpose of conducting a risk analysis must be specified before the risk assessment is performed. This thesis aims to investigate how the risk differs from one S-CCS type to another. It is, therefore, not necessary to deeply investigate risks that do not vary between the different closed cages but instead focus on events and elements where risk differs between the systems.

It is also necessary to enlighten the purpose of the risk assessment and what the analysis is meant to be used for. What the users of the results want to know from the assessment is a question that should be answered. This thesis aims to provide a guideline for which structures are most suitable for different degrees of exposure from a risk perspective. The assessment is intended to be a tool for risk-based design of floating semi-closed containment systems in an early design phase.

3.1.2 Step 2: Identify hazards and hazardous events

The purpose of step 2 is to identify and list hazardous events for all the system elements that were listed in step 1. A structured brainstorming with a background in the literature study provides an outline of all the relevant hazardous events for the different systems and system elements. From the brainstorming process, there will be an extensive list of potential hazards and hazardous events. The list is reduced by removing hazards and hazardous events with obviously low risk. This is to save time and not perform the time-consuming analysis of negligible risks.

The final list is structured, and each of the hazardous events is categorized to understand what could occur, when it may occur, and for some events, where it will occur. Structuring and categorizing the list is beneficent for the next steps. It will provide a better overview and make the analysis easier to conduct.

Some hazardous events that are removed from the list should still be evaluated or given a comment on why the events are kept out of the PHA. As the objective of this thesis was to understand the change of risk for different structures and for different exposure, some events where the risk is not affected by site or structure are removed from the PHA sheet. These events will be further described and documented.

3.1.3 Step 3: Determine the frequency of hazardous events

Step three of the preliminary hazard analysis aims to estimate the frequency of the different outcomes sorted out in step 2. Frequency is often based on statistics from historical data, expert opinions, and estimations about the future. Since the S-CCS technology is new and not much used, the amount of historical accident data is missing. The frequency of hazardous events is mostly based on expert judgments and own interpretation of the risks.

The hazardous events are given a frequency number between one and five, where the number five is the most frequent and one is extremely rare. The frequency categories are defined as shown in Table 3.1.

Category	Frequency (per year)	Description
5 - Fairly normal	$10 - 1$	Events that are expected to occur frequently.
4 - Occasional	$1 - 0.1$	Events that happens now and then, and will normally be experienced by the personell.
3 - Possible	$10^{-1} - 10^{-2}$	Rare event, but will possibly be experienced by the personell.
2 - Remote	$10^{-2} - 10^{-3}$	Very rare event that will not necessarily be experienced in any similar plant.
1 - Improbable	$10^{-4} - 0$	Extremely rare event.

Table 3.1: Category and description of the different frequencies

3.1.4 Step 4: Determine the Consequence of Hazardous Events

Step four is carried out together with step three to find the potential consequences of the hazardous events and the frequency of the different consequences. A hazardous event might have, and probably will have the potential to result in several different outcomes with a varying probability of occurrence. The link between consequence and frequency is essential to be able to estimate the risk and give a realistic picture.

The different outcomes are given a rank between one and five based on the severity. The most severe outcomes are ranked with higher numbers, and minor accidents are ranked low. The risk analysis for this thesis contains several categories of outcomes and therefore requires a ranking description of the different consequence types. The semi-closed containment systems there have been focused on five consequence types. These types are listed below.

- Structural damage
- Escapes
- Fish welfare
- Lice
- Environment

Rausand and Haugen (2020) have proposed a classification of the consequence based on the degree of severity concerning environmental impact and structure or property. This classification is further used for evaluating the risk of the different S-CCS for the degrees of exposure when it comes to environmental and structural hazards.

	Consequence type	
Category	Environment	Structural damage
5 - Catastrophic	Time for restitution of ecological resources $>= 5$ years	Total loss of system and major damage outside system area
4 - Severe loss	Time for restitution of ecological resources= 2–5 years	Loss of main part of system; production interrupted for months
3 - Major damage	Time for restitution of ecological resources $<= 2$ years	Considerable system damage; production interrupted for weeks
2 - Damage	Local environmental damage of short duration ($<= 1$ month)	Minor system damage; minor production influence
1 - Minor damage	Minor environmental damage	Minor property damage

Table 3.2: Classification of environmental and structural consequences according to their severity.

Regarding escapes, the consequence classification is based on the amount of escaped salmon resulting from a hazardous event. NS-9415 (2021) have proposed a consequence classification with respect to escapes, which could be seen in Table 3.3.

Consequence classification - Escapes of salmon	
Category	Escapes
5 - Catastrophic	>500 000
4 - Severe loss	150 000 <X <500 000
3 - Major damage	10 000 <X <150 000
2 - Damage	100 <X <10 000
1 - Minor damage	<100

Table 3.3: Consequence classification of salmon escapes according to the severity.

There is a strong link between lice problems and fish welfare, and the consequence classification of both categories is therefore sharing a joint classification. Classification of the consequences of fish welfare and lice problems are inspired by the risk analysis made by SalMar (2021) and is shown in Table 3.4 below.

Consequence classification	
Category	Fish welfare and Lice
5 - Catastrophic	Serious/extreme/acute mass mortality or welfare incidents causing significant suffering
4 - Critical	Long-lasting impact/irreversible stress or physical injury. Prolonged high mortality or injury/disorder. Example: High accumulated mortality or welfare events that affect welfare(injury)
3 - Major impact	Persistent adverse effects (ex: notifiable diseases), recurrent efffects. Abnormal mortality (0.75% per week).
2 - Minor impact	Longer moderate effect, illness or stress. Ex: increased mortality (0.2% per week)
1 - Harmless	Short-lasting effect, stress. Reversible.

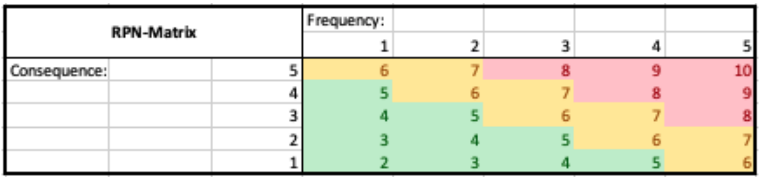
Table 3.4: Classification of consequences regarding fish welfare and lice challenges according to severity.

3.1.5 Step 5: Suggest Risk Reducing Measures

After determining the frequency and consequence, suggestions for risk-reducing measures should be made if possible. The risk-reducing measures are divided into two parts, with one being frequency-reducing measures and the other consequence-reducing measures. The frequency-reducing measures are suggested to reduce the risk of hazardous events occurring. These are measures that are more important for events with a higher probability of transpiring. The consequence-reducing measures are barriers suggested to mitigate the severity of the outcomes if a hazardous event occurs. Such barriers are most important for events with severe outcomes.

3.1.6 Step 6: Assess the Risk

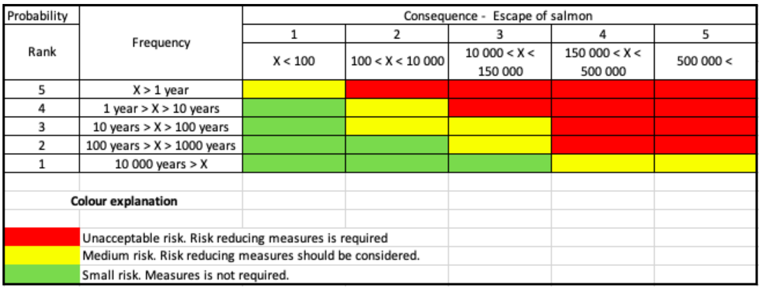
The next step is to evaluate the risk when the frequencies and consequence ranking are set for all the hazardous events. Based on the ranking of the frequency and consequence, a risk priority number(RPN) for each event is calculated by summarizing frequency and consequence. By use of a risk matrix, the hazardous events and their outcomes could be placed within three risk groups based on the likelihood and severity. The risk grouping consists of broadly acceptable risk, acceptable risk - but should be made as low as reasonably possible and unacceptable risk where risk reduction is required. An illustration of an RPN matrix is shown in Figure 3.2, but the matrices vary depending on the type of consequence, i.e., whether it is structural damage, escape or fish welfare.



RPN-Matrix			Frequency:				
			1	2	3	4	5
Consequence:		5	6	7	8	9	10
		4	5	6	7	8	9
		3	4	5	6	7	8
		2	3	4	5	6	7
		1	2	3	4	5	6

Figure 3.2: Illustration of a risk matrix where green areas represents broadly acceptable risk, yellow area represents acceptable risk - but should be made as low as reasonably possible, and red area represents unacceptable risk where risk reduction is required.

Escapes are one of the major challenges for Norwegian aquaculture, and the motivation for enclosing the production systems a new RPN matrix for escapes is made. The matrix is inspired by NS-9415 (2021), where the limit for acceptable risk is more strict. Lower frequencies and less severe consequence numbers are required to produce at an acceptable risk level as shown in Figure 3.3.



Probability	Frequency	Consequence - Escape of salmon				
Rank		1	2	3	4	5
		X < 100	100 < X < 10 000	10 000 < X < 150 000	150 000 < X < 500 000	500 000 <
5	X > 1 year	🟨	🟥	🟥	🟥	🟥
4	1 year > X > 10 years	🟩	🟨	🟥	🟥	🟥
3	10 years > X > 100 years	🟩	🟨	🟨	🟥	🟥
2	100 years > X > 1000 years	🟩	🟩	🟨	🟥	🟥
1	10 000 years > X	🟩	🟩	🟩	🟨	🟨
Colour explanation						
🟥	Unacceptable risk. Risk reducing measures is required					
🟨	Medium risk. Risk reducing measures should be considered.					
🟩	Small risk. Measures is not required.					

Figure 3.3: RPN-matrix for fish escapes from a S-CCS.

3.1.7 Step 7: Report the Analysis

For reporting the PHA, the analysis should be presented so that the results can be used for safety management and give an understandable insight into which production system mitigates the risk of salmon production. The results are presented in a PHA worksheet that gives a good overview of the risk picture for the system parts or system elements of a S-CCS and the possible outcomes of a hazardous event. An example of a PHA worksheet setup is shown in Table 3.5.

System element	Hazard/ threat	Nr.	Hazardous event (what, where, when)	Cause (triggering event)	Consequence (harm to what?)	Risk			Risk reducing measures		Category	Comment
						Freq.	Cons.	RPN	Frequency	Cnsequence		
System element 1	Hazard 1	1	Event 1	Triggering event 1	Consequence 1	2	3	5			X	
System element 2	Hazard 2	2	Event 2	Triggering event 2	Consequence 2	1	3	4			X	

Table 3.5: Example of a Preliminary Hazard Analysis worksheet.

As shown in Table 3.5, the PHA worksheet starts to address which system component of the S-CCS that is analysed. Further, the investigated hazards and hazardous events for the respective system element are sorted. There could be several hazards and hazardous events for each system element. To understand why the hazardous events occur, a set of triggering events are proposed. The triggering events are often connected with the suggested risk reducing measures as they are the initiating cause of the undesirable event. The hazardous event could have several different outcomes with varying severity. Possible consequences of the event are listed in the consequence column, which are further given frequency and consequence rankings leading to the risk priority number. If possible or realistic, risk reducing measures are suggested. These suggestions either falls within frequency reducing measures or consequence reducing measures. However, some of the measures could be difficult to place as they could fall within both groups. An additional column have been made to make it easier to see which type of consequence the event affects i.e if the consequence has an impact on the environment, structure or any of the other consequence types. The last column is for commenting the analysis if necessary.

3.2 Comparative Analysis

In order to justify which of the three S-CCSs is most suitable for a specific wave exposure, it is necessary to compare the risks. Comparing PHA results will give insight into how the risk differs from one system type to another. The comparative analysis looks at each of the listed system components. It enables information on how the system components for flexible, semi-rigid, and rigid are ranked for the different consequence types according to the risk.

Risk priority numbers have been made for each hazardous event and its possible outcomes. In addition, the consequences have been categorized as an impact on structural damage, escape, lice, fish welfare, or the environment. The average RPN for the categories is calculated for each system component. The average rank is used to compare how the risk picture changes using different structural types.

The comparison results are placed in a matrix to structure the results and give an easier reading for the users of the results. An example of the matrix is shown in Table 3.6 below.

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
System component 1	Structural damage	x	x	x
	Escapes	x	x	x
	Lice	x	x	x
	Fish welfare	x	x	x
	Environment	x	x	x

Table 3.6: Comparative analysis matrix

It is essential to state that this method only gives average risk pictures. There might be some hazardous events for one of the systems at one of the components that have unacceptable risks but are hidden in the average RPN. Stating a conclusion based on the comparative analysis alone is insufficient for understanding the whole risk picture.

3.3 Change Analysis

To investigate how the risk changes as a result of using other sites with different wave exposure, a change analysis proposed by Rausand and Haugen (2020) is used. Change analysis is mainly used to investigate how potential modifications to a known system or process will affect the risk. However, the system is also applicable for situations where the system operating practices are changed. The analysis is a helpful tool to identify the effects of changing location with a following change of exposure. The method focuses on the key differences and the events where risk deviates the most. The change analysis contains five main objectives

1. Identify the key differences when changing location to a more exposed or less exposed area.

2. Determine the effect of the key differences.
3. Identify the main system vulnerabilities caused by the difference.
4. Determine the risk impact of the differences.
5. Identify new risk reducing measures or barriers to control the risk.

From the preliminary hazard analysis, risks for the systems at moderate exposure have already been established. This sets the base for the change analysis. The investigations are conducted by changing the location of the systems to more and less exposed areas and addressing how these changes affect the old risk, i.e., for moderate exposure. The preliminary hazard analysis has already proposed the fifth objective regarding risk-reducing measures. Most of the risk-reducing measures are suitable regardless of location. Therefore, the fifth objective is substituted with comparing the old risk and the new risk given the change. The comparison should be presented with the old frequency, consequence, and RPN and the new frequency, consequence, and RPN. The RPN numbers are compared, and a delta risk is established, showing the percentage change of RPN for the different sites.

Chapter 4

Risk analysis and preliminary results

As stated in earlier chapters, there is a need for new technology to increase Atlantic salmon production in Norway. Some of the proposed solutions are semi-closed containment systems in the sea. There are different strategies when it comes to the structural design of these systems. Developed and planned constructions are divided into three structural properties based on material. These are flexible structures, semi-rigid structures, and rigid structures. The technologies are relatively immature, and the risk of using these systems are not fully known yet.

4.1 Preliminary hazard analysis

Plan and prepare

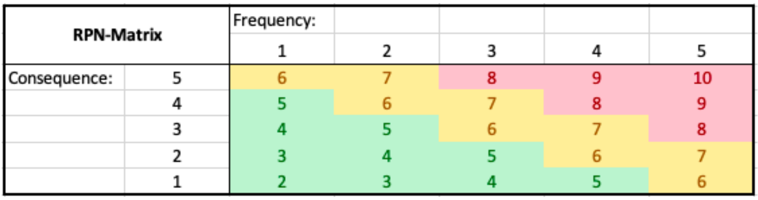
To investigate how the risk differs from using different types of structures when producing salmon in S-CCS, a risk analysis was performed. Investigation of the different structures in locations with moderate exposure is conducted in PHA and is further used as the initial risk in the change analysis. The goal of the thesis is to investigate how the risk varies between the structures and their main system components. The main components of the structures are implemented in the analysis. The investigated system components for all three types of S-CCS are

- Water inlet;
- Water outlet;
- Structure/Wall;
- Floater/buoyancy;
- Dead fish pump

The hazardous events are given a frequency- and consequence number, which together make the risk priority number. All hazardous events and outcomes are categorized as harm to, or due to, either

- Fish welfare
- lice
- structural damage
- escapes or
- environment.

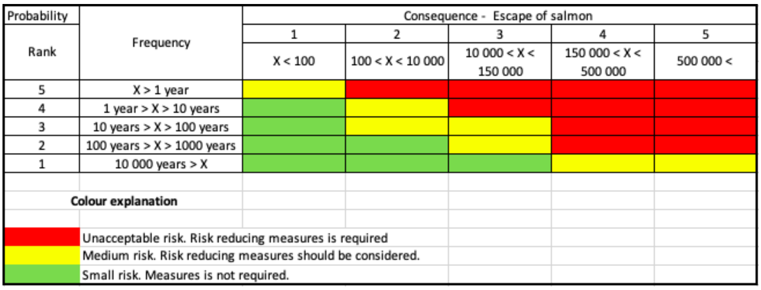
The events could be placed in an RPN matrix that enlightens the risk and defines where the transition from broadly acceptable to acceptable within the ALARP area or from the ALARP area to unacceptable risks. All consequence categories, except escapes, use the matrix proposed by Rausand and Haugen (2020) shown in Figure 4.1 below. The green area represents the broadly acceptable area, the yellow represents the ALARP area, and the red represents an unacceptable risk.



RPN-Matrix		Frequency:				
		1	2	3	4	5
Consequence:	5	6	7	8	9	10
	4	5	6	7	8	9
	3	4	5	6	7	8
	2	3	4	5	6	7
	1	2	3	4	5	6

Figure 4.1: Risk priority number matrix proposed by Rausand and Haugen (2020).

Escapes are one of the major challenges regarding aquaculture. NYTEK and NS 9415 have taken measures to reduce the number of escapes from Norwegian fish farms. They have proposed an RPN matrix. The RPN matrix in Figure 4.2 are inspired by the matrix made by NS 9415 and further used in this thesis.



Probability Rank	Frequency	Consequence - Escape of salmon				
		1	2	3	4	5
		X < 100	100 < X < 10 000	10 000 < X < 150 000	150 000 < X < 500 000	500 000 <
5	X > 1 year	🟨	🟥	🟥	🟥	🟥
4	1 year > X > 10 years	🟩	🟨	🟥	🟥	🟥
3	10 years > X > 100 years	🟩	🟨	🟨	🟥	🟥
2	100 years > X > 1000 years	🟩	🟩	🟨	🟥	🟥
1	10 000 years > X	🟩	🟩	🟩	🟨	🟨

Colour explanation

🟥	Unacceptable risk. Risk reducing measures is required
🟨	Medium risk. Risk reducing measures should be considered.
🟩	Small risk. Measures is not required.

Figure 4.2: Risk priority number matrix for escapes inspired by NS 9415(NS-9415, 2021)

The matrices in Figure 4.1 and Figure 4.2 sets the limit for what is an acceptable and unacceptable risk and which hazardous events need risk-reducing measures to maintain a safe operation.

System components such as oxygen supply, power systems, monitoring of water quality, and current inducers are not included in the system element part of the PHA as the risk is assumed to be relatively similar for all three types of S-CSSs. However, some of them are mentioned as they could cause failures of the listed components. In addition, mooring systems are neither included as a system component in the analysis but are mentioned in the risk picture for some hazardous events and possible outcomes. All investigated system components identified a set of hazards and hazardous events. The three structures of S-CCS are first investigated individually using the PHA.

4.1.1 Flexible semi-closed containment system

Water inlet

In past experiences using flexible S-CCS, there have been some problems with water inlet systems. A list of hazards and the following hazardous events have been identified based on historical failures and challenges. In addition, other possible events have been listed from a brainstorming process. For water inlet pumps and water inlet pipes, different hazards and hazardous events are listed in the PHA shown in Appendix A.

The first listed hazard is fouling or blockage of the inlet, which could result in the hazardous event of reduced water exchange. Insufficient water flow could lead to severe outcomes. To provide a healthy environment where fish can grow and fish welfare is maintained, adequate water exchange is decisive. Reduced water exchange would lead to an increased concentration of CO2, solid waste from feed and feces, and total nitrogen ammonia(TAN). The self-cleaning ability of the S-CCS is dependent on internal currents from inlet water. The risks are considered acceptable risks but within the as low as reasonably possible(ALARP) area, meaning that risk-reducing measures should be taken.

The second hazard with respect to water inlet systems is technical errors. A technical error might lead to reduced or fully stopped water inlet pumps. A pump stop could be caused by several incidents, such as power failure or human errors, and the outcomes could have a large impact on production. In addition to the consequences listed above regarding fish welfare, there are also some structural challenges. The flexible fabric is dependent on overpressure to maintain a fully inflated form. Over-pressure could be lost if the pumps stop, causing deformations of the bag. In the PHA in Appendix A, two possible outcomes of deformations due to pump stop are listed. One is that the production volume is reduced, causing stress for the fish and disrupting the self-cleaning ability of the system. As a result, there might be higher fish densities using more oxygen(Kristiansen et al., 2018) and an increased amount of total suspended solids(TSS). Deformations of the bag due to pump stop could also potentially lead to increased drag force on the structure. A deflated bag will experience larger drag forces compared to an inflated bag. The bag will form a parachute-like formation which could increase the drag force by up to 2,5 times compared to an inflated bag, dependent on the filling level(Lader et al., 2015). A possible consequence might be damage to the material or mooring lines. The risk for both outcomes falls within the ALARP area.

The risk of parasites, organisms, or pathogens entering the system is within the ALARP area for all three types of S-CCS. With UV treatment of the inlet water and water pumped from large depths, the risks of pathogens and parasites are very low. However, there have been experiences where jellyfish have entered the systems, increasing mortality drastically. As a result, the hazardous event of parasites, organisms, and pathogens entering the system fall within acceptable risk, but risk reduction measures should be developed. Both frequency and consequence-reducing measures are proposed. To reduce frequency of occurrence, it is suggested to mount a barrier at the pipe opening, to keep jellyfish or other organisms from entering. To reduce the consequence, there is suggested to have a rapid inspection of the fish in order to discover problems at an early stage.

The last item on the list of hazards for water inlets is weather/sea and operating vessels. The hazardous events are large forces from wind, sea, or impacts with vessels causing damage or destruction to water inlet pipes. The water inlet systems for flexible structured S-CCS are less sheltered from external forces such as waves, currents, and vessels as they are mounted on the floaters or walkways in the system design(Clarke et al., 2018). In moderate exposure, the risk of causing damage or destruction to the water inlet pipe is classified as an acceptable risk but just below the unacceptable risk. This calls for risk-reducing measures. The proposed frequency-reducing measures is to design the pipes for larger loads and, if possible, implement protection in the design of the S-CCS.

Water outlet

Some S-CCS have regulating water outlets. For those, technical and human errors are potential hazards that can affect the water flow out of the system. Lack of attention or competence for operators is triggering events that could lead to hazardous events of losing over-pressure inside the bag. Over-pressure is necessary to maintain an inflated shape of the bag, ensuring enough space for the fish to swim freely. Moreover, a deflated bag will cause multiple times larger drag forces on the bag due to a parachute-like deformation(Lader et al., 2015). As shown in Appendix A the risk of affecting fish welfare and increasing drag forces are acceptable within the ALARP area. Risk-reducing measures to ensure an inflated form of the bag could be stiffeners in the structure.

Large loads from rough seas acting on the water outlets will cause stress to the component and the filtration system within. Damaging the filtration systems mitigate the waste collection efficiency or disable the collecting ability of the system leading to releases of sludge to the environment. The risks of such damages are broadly acceptable with relatively low risk and a low degree of severity. However, if the damage to the outlets becomes too severe, the risk of escapes occurs. Frequency is lower, but with more serious outcomes leading to risks within the ALARP area as shown in Appendix A.

Dead fish and solids might block the water outlets resulting in a reduced flow through the system. It will have a negative effect on the water quality inside the cage, reducing the fish's welfare. The frequencies of such events are relatively low but will drastically affect the health and welfare of the fish. Risk-reducing measures should be considered, where increased maintenance and inspection will help reduce the frequency of occurrence.

Structure: Flexible bag

Using a flexible bag to enclose the production volume comes with some challenges. The flexible material brings with it some risks that are unique for these types of systems. The motion and behavior of the bag in waves and currents are different compared to semi-rigid and rigid structures. The PHA shown in Appendix A lists four hazards and hazardous events with several possible outcomes.

The first hazard is the bag's motion in combination with sharp edges on the dead fish pump and other equipment mounted on the bag. Following the hazardous event, such motions close to equipment cause damage to the material. The consequences of such damages could be a stop in production to repair or a change of cloth, or a large rift causing escapes if severe enough. Damages causing a need for repair are classified as frequency rank three and consequence rank three, which is an acceptable risk. However, precautions regarding design to avoid sharp edges should be made. The internal excess pressure will cause a discharge of contained water if damage causing a hole in the bag occurs. Discharge may lead to draining the bag's contained water, which can be critical for closed flexible cages (Kristiansen et al., 2018). Outcomes, where a rift in the bag causes large amounts of escapes, are considered a less frequent happening. However, the consequence is more severe, resulting in an unacceptable risk since the risk allowance criteria of escapes are more strict. Risk-reducing measures must be implemented. In addition to the frequency-reducing measure of designing equipment without sharp edges, a consequence-reducing measure is proposed. Mounting a safety net outside the bag as double security against escapes is suggested to reduce the risk of escapes. This method is much used for the already existing floating flexible cages.

Another hazard is human errors during the collection of fish for further transportation to the grow-out phase that could potentially cause injuries to the fish or damage to the material during the operation. The flexible structure makes it more challenging to implement internal collection systems in the design. Escapes and injury during the collection of fish are both considered acceptable risks within the ALARP area. The cause of human errors might be a lack of training or lack of attention for the operators. Therefore, good and well-worked procedures are suggested as a frequency-reducing measure. A proposal to reduce the risk of escapes is double security regarding escapes in the form of a safety net to reduce the consequence of human errors.

As stated earlier, flexible S-CCS behave differently in waves and currents compared to a semi-rigid and rigid structure. When exposed to larger wavelengths and steeper waves, the fabric develops wavelike motions in the top that propagates towards the bottom of the bottom parts of the bag. As a result, large snap loads could potentially damage the fabric(Mukhlas et al., 2021). These loads can cause stress and fatigue on the material. Possible outcomes of snap loads are damage over time, causing a need for maintenance, or worse, loss of structural integrity and possibly escapes. There should be proposed strategies for reducing the risk of structural damage as the risk is within the ALARP area of the risk acceptance criteria. Regarding escapes, the frequency of occurrence is assumed to be less frequent, but the severity of the outcome contributes to making the event contain an unacceptable risk. Double security against escapes is suggested to reduce the risk of salmon escapes.

One of the major concerns regarding enclosing the fish cage is sloshing. Waves with periods close to the natural sloshing period will generate internal waves inside the systems. These internal waves might grow to an extent where both structure and fish could take damage from the forces. During testing, results have shown that sloshing is more prominent for more rigid cages, while the flexible cage experience less sloshing(Sintef, 2018). However, sloshing is still a challenge for flexible cages. The consequential outcomes of structural damage and reduced fish welfare are within the ALARP area. To reduce the risk, design and eigenperiods of the system are central. The system should be designed to have a relatively high eigenperiod, to prevent resonance.

Buoyancy and floaters

Floaters are a critical system component, as the floaters keep the systems afloat. For a flexible structure, the material has little to no reserve buoyancy. Heavy equipment and fouling are hazards that could reduce the freeboard. Reduced freeboard combined with larger incoming waves could result in hazardous events where untreated water containing lice, other parasites, or pathogens enter the system over the floating collar. In moderate exposure, the risk of infection of parasites or diseases due to water entering over the collar is considered within the ALARP area, as shown in Appendix A. Several risk-reducing measures are proposed. Designing the S-CCS with an enclosed roof or with plexiglass around the floating collar will reduce the frequency of occurrence. While increasing the inspection of fish will discover infections or illnesses at an early stage and potentially reduce the severity of the outcomes. Regarding escapes over the floating collar, the risk is broadly acceptable with no need for risk-reducing measures.

Other hazards for the floaters of a S-CCS are well boats or other operating vessels. Several factors could influence the maneuvering of these vessels close to the systems. Tricky wind, large waves, and strong currents could be contributing factors to inducing the hazardous event of significant power impact between vessels and floaters. In addition, lack of crew training or attention could be an underlying factor. Impacts with minor damages on the floaters are occasional events with a low degree of severity. While more severe events where considerable damage is less frequent. These events are considered acceptable risks, but risk-reducing measures should be taken. Improved procedures for operating vessels close to the systems are suggested. Mounting impact dampers on the outside of the floaters could reduce the risk of damaging the structural component.

Dead fish pump

The dead fish pump transports dead fish and solid waste out of the system from the bottom of the bag to the surface for further processing. In already developed flexible systems, dead fish pipes are mounted outside the structure. The pipes are exposed to forces from waves, currents, and potential vessels operating at the facility and are therefore listed as hazards. Interaction with these hazards could result in unwanted events where the dead fish pipe is damaged. As shown in Appendix A several outcomes are listed. Risk-reducing measures should be provided as the risk of some of the potential outcomes falls within the ALARP region. Clogged pipes or reduced flow due to larger deformations from external forces might occur, and the worst case is that the pipes are torn off. Implementing a dead fish pump system where the components are protected in the design will benefit the risk picture.

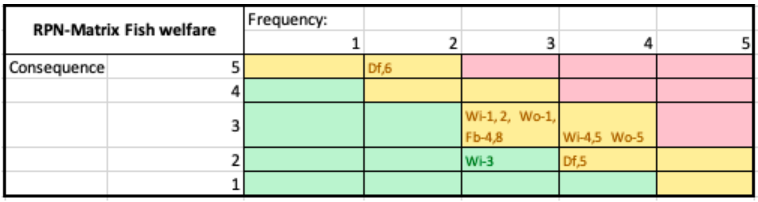
Another hazard is technical errors leading to reduced effect or entirely stopped pumps. However, such events' risks are considered the same for flexible, semi-rigid, and rigid systems. Risk-reducing measures are to increase maintenance and monitoring. Also, implementing redundant power systems will secure a safer operation.

Risk priority numbers and RPN-matrices

The identified hazards and hazardous events presented in Appendix A and described above have outcomes that affect one of the consequence types discussed earlier. The results from the preliminary hazard analysis are presented in RPN matrices to give a better picture of the risk regarding the consequence types. The outcomes of the hazardous events for each of the main components are numbered on the PHA sheet. The component and numbering are placed in the matrix based on the frequency number and consequence number, making it a broadly acceptable risk, acceptable within the ALARP area, or unacceptable risk. The components are given abbreviations as shown in the list below

- Water Inlet = Wi
- Water Outlet = Wo
- Flexible bag/Structure/wall = S(for semi-rigid and rigid) and Fb(for Flexible bag)
- Buoyancy/floater = B
- Dead fish pump/pipe = Df.

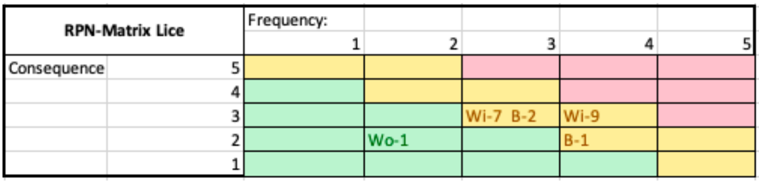
For a flexible S-CCS operating at moderate exposure, the risks concerning fish welfare are mainly within the ALARP area except for outcome number 3 for water inlets in Appendix A.



RPN-Matrix Fish welfare		Frequency:				
		1	2	3	4	5
Consequence	5		Df,6			
	4					
	3			Wi-1, 2, Wo-1, Fb-4,8	Wi-4,5 Wo-5	
	2			Wi-3	Df,5	
	1					

Figure 4.3: RPN matrix for fish welfare in a flexible system

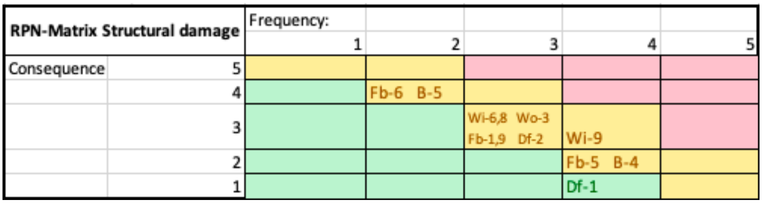
The risk of lice entering the system is mainly affected by hazards threatening the structure's water inlet, water outlet, and buoyancy. The risks fall within the ALARP area and the broadly acceptable area, as shown in Figure 4.4. For a flexible S-CCS operating at moderate exposure, the risks concerning fish welfare are mainly within the ALARP area except for outcome number 3 for water inlets in Appendix A.



RPN-Matrix Lice		Frequency:				
		1	2	3	4	5
Consequence	5					
	4					
	3			Wi-7 B-2	Wi-9	
	2		Wo-1		B-1	
	1					

Figure 4.4: RPN-matrix for lice in a flexible system

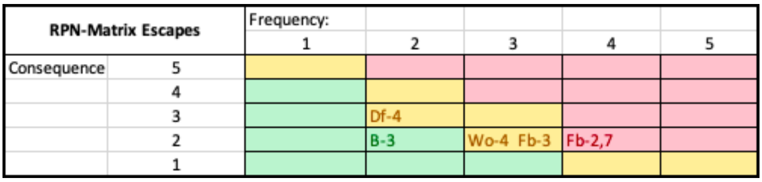
As seen in Figure 4.5 many hazards make a threat to the flexible bag when operating at moderate exposure. However, all the hazards, hazardous events, and their respective outcomes are considered acceptable risks, mainly within the ALARP area. The risk-reducing measures proposed above should be taken into account to make the risk as low as reasonably possible.



RPN-Matrix Structural damage		Frequency:				
		1	2	3	4	5
Consequence	5					
	4		Fb-6 B-5			
	3			Wi-6,8 Wo-3 Fb-1,9 Df-2	Wi-9	
	2				Fb-5 B-4	
	1				Df-1	

Figure 4.5: RPN-matrix for structural damage on a flexible system

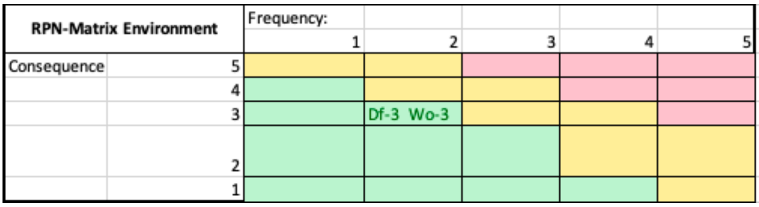
From the PHA, there are found two events leading to escapes where the risk is unacceptable. Both events are related to the flexible bag enclosing the production volume. As seen in Figure 4.6 the outcomes number 2 and 7 in Appendix A for the flexible bag. Risk-reducing measures must be taken. Possible risk-reducing measures were proposed earlier.



RPN-Matrix Escapes		Frequency:				
		1	2	3	4	5
Consequence	5	🟨	🟥	🟥	🟥	🟥
	4	🟩	🟨	🟥	🟥	🟥
	3	🟩	Df-4	🟨	🟥	🟥
	2	🟩	B-3	Wo-4 Fb-3	Fb-2,7	🟥
	1	🟩	🟩	🟩	🟨	🟨

Figure 4.6: RPN-matrix for escapes in a flexible system

There are two of the listed hazards that could potentially harm the environment. These are outcome number 3 for the dead fish pump system and outcome number 3 for the water outlet pipe in Appendix A. Both are broadly acceptable risks, as seen in Figure 4.7.



RPN-Matrix Environment		Frequency:				
		1	2	3	4	5
Consequence	5	🟨	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	Df-3 Wo-3	🟨	🟨	🟥
	2	🟩	🟩	🟩	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨

Figure 4.7: RPN-matrix for environmental impact for flexible systems

4.1.2 Semi-rigid semi-closed containment system

The results of the preliminary hazard analysis for semi-rigid structures operating in moderate exposure is shown in Appendix B.

Water inlet

The designed water inlet system for semi-rigid cages is often quite similar to flexible cages. Water inlet pipes are mounted outside the structure, exposing the pipes to external loads from waves and currents. When it comes to risks regarding blockage and fouling of the inlets causing reduced water entry flow, it is considered to be similar to flexible systems. Increased inspection of the fouling conditions of the water inlet is a suggested risk-reducing measure. It will ensure that fouling does not reach such severity that the flow is reduced.

Technical errors in the water inlet pumps will affect the water quality inside the cage and negatively impact fish welfare. The pumps are critical for water exchange to provide a suitable environment for fish to grow and live. The risk of technical errors leading to hazardous events where the pump efficiency is reduced or the pump stops is considered acceptable. To reduce the risk, even more, increasing inspection and monitoring of the critical parts of the pump system are suggested. Unlike the flexible system, a semi-rigid structure will not deform and mitigate the production volume due to reduced overpressure.

As mentioned in section 2.4 there have been accidents leading to the destruction of water inlet pipes. One accident occurred on the semi-rigid S-CCS called Aquadome during a storm. Strong wind and large waves caused forces acting on the system that exceeded the designed loads for the pipes. Therefore strong wind and waves are listed as hazards in Appendix B. The outcomes could be damage or destruction of the inlet pipes, with risks considered within the ALARP region. By designing protection of the inlet pipes, the risk could mitigate. Aquafarm Equipment's S-CCS Neptune has implemented support for water inlet pipes in their design(Aquafarm).

Water outlet

Technical errors leading to reduced flow out of the cage have a low frequency of occurrence, as seen in Appendix B, but such failures will severely affect the water quality. For long-lasting failures, the low water quality will lead to mortality among the fish. The high severity of outcomes makes the risk considerable within the ALARP area. Constant monitoring and redundant backup systems are suggested measures to reduce the risk.

The outlets are relatively open to forces from the seas. Over time, rough seas and strong currents will cause wear and tear on the component and filtration within. In the worst case, the wear and tear on the outlets cause such damage that the outlet loses structural integrity, and fish escapes occur. The frequency is low, but with the strict risk criteria of escapes, the risk is within the ALARP level. Barriers mounted outside the outlets to prevent fish from escaping are suggested as a consequence-reducing measure.

Also, blockage of the water outlets is a considerable risk. The frequency is low, but the effect on water exchange has potentially severe outcomes. Reduced flow through the system allows for more particles and an increasing concentration of toxic gasses in the contained water. More rapid inspection intervals and maintenance intervals are proposed solutions to mitigate the risk of blocked outlets.

Structure

Well-boats and other operating vessels on and around the system may cause hazardous events where there could be large power impacts between vessels and the cage. Impacts causing minor damage are assumed to be fairly normal, while significant impacts causing considerable damage are rare. The severity of the outcomes could be many and varying but still considered an acceptable risk. The risk of events involving these damaging impacts is within the ALARP area, and measures to reduce the risk could be improved procedures and training for the crew. Impact dampers on the floater could also reduce the loads on the structure.

In past experiences, bad weather and rough sea have damaged semi-rigid and rigid structures. At locations with moderate exposure, the structures are relatively exposed to large loads from sea and wind during periods. There are some concerns surrounding semi-rigid and rigid closed containment systems. From an engineering point of view, these concerns are based on whether solid walls can withstand forces from the currents and waves over time(Chadwick et al., 2010). Potential hazardous events of such loads could be that the structure loses structural integrity, resulting in fish escapes and releasing sludge and dead fish into the environment. Concerning escapes, the risk is considered unacceptable, and risk-reducing measures are necessary. The structure should be designed for more extreme loads and mount double security against escapes. A safety net could be mounted on the inside or outside of the structure to prevent fish from escaping if cracks develop in the structure.

A major hazard regarding closed cages is certain wave periods and sea states that could lead to events where sloshing develops inside the tank. According to Sintef (2018), semi-rigid cages will experience more sloshing motions compared to a flexible structure. Incoming waves with periods close to the natural period could potentially harm fish and affect fish welfare. It might affect the structure's horizontal motion and cause stress and fatigue in the cage wall(Chu et al., 2020). Two possible outcomes in the PHA are shown in Appendix B. These are reduced welfare and considerable damage to the structure. The hazardous events and possible outcomes are considered to be within the ALARP area. To reduce the risk of sloshing, the system must be designed for large eigenperiods to avoid resonance in waves. Another possibility is to reduce the free surface. Hauge Aqua uses this method in their concept Egget(Aqua, 2022).

Buoyancy and floaters

Buoyancy from floaters is vital for the system to stay afloat and maintain sufficient freeboard. A semi-rigid structure will have little reserve buoyancy from the structure wall compared to rigid cages. Fouling on the structure and heavy equipment mounted on the walkways will affect the freeboard. Combined with waves, these are listed as hazards for the S-CCS, which could lead to hazardous events where water splashes over the top of the structure. Untreated water containing lice or larvae could enter the system, causing minor problems and more severe outcomes of lice spreading and infecting the fish. Minor problems are more likely to occur more frequently with a lower degree of severity, while infections calling for treatment are less frequent. The risk is acceptable, but risk-reducing measures should be provided. To reduce the frequency of occurrence, the floaters could be designed with larger cross-sections by enclosing the roof or mounting a barrier around the floater. The barrier could be plexiglass on the outside of the walkways. A measure to reduce the consequence is a more rapid inspection of fish to discover infections at an early stage.

Well boats or other operating vessels on and around the S-CCS poses a risk of impacts with the structure. In moderate exposure, difficult maneuvering conditions could be a contributing cause of hazardous events occurring. In addition, a lack of training for the crew could influence the operations. As a result, the floaters might catch damage from a possible impact between the vessels and the floating structure. Events leading to minor damage are considered a broadly acceptable risk in Appendix B as the severity of the outcome is low. However, due to the severity, events leading to loss of buoyancy and structural integrity fall within the ALARP region. Better training for crew and well-made procedures when operating on or close to the production system are suggested risk-reducing measures to reduce the frequency of hazardous events. Impact dampers mounted on the floaters could reduce an impact's damage, potentially mitigating the consequence.

Dead fish pumps and pipes

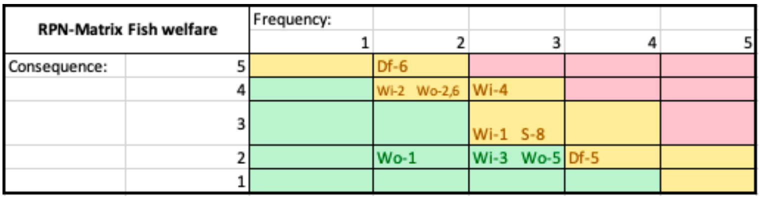
Most of the existing flexible and semi-rigid S-CCSs that have been made are designed with dead fish pumps mounted at the bottom of the structure. The pipes for transporting the sludge and dead fish are located outside the closed wall. This comes with a risk when hazards like currents, waves, or operating vessels are working on the pipes. This could potentially cause damage to the dead fish system resulting in unwanted outcomes. It could be minor damages, deformation, or, worst case, torn-off dead fish pipes. Minor damage will not affect the system considerably, with a following low risk. Furthermore, deformations of the pipes could result in clogged pipes making transportation of sludge and dead fish less effective, causing reduced water quality with a higher concentration of particles and increasing TAN. The risk for all potential outcomes is assumed to be broadly acceptable, but risk-reducing measures are proposed due to uncertainty. In the design, dead fish pumps could be protected from the surrounding environment by implementing a structure around the pipe systems. Another possible solution could be to place the pipe system within the cage.

The transportation of sludge out of the system is crucial to providing a healthy environment for fish. Technical errors are hazards that may occur. A technical error on the dead fish pump could potentially lead to hazardous events where the pump stops. If sludge stays in the system for too long, toxic gasses evolve, and increased particles in the water could affect the health of fish inside the cage. The probability of experiencing technical errors is assumed to be the same for all systems and within the ALARP risk classification. Redundant power systems, maintenance of critical parts, and constant monitoring of the pumps are suggested risk-reducing measures to mitigate the risk.

Risk priority numbers and RPN-matrices

Same as for the risk analysis of a flexible system, RPN matrices for semi-rigid systems are made to present the result of the analysis. The components and outcome numbers from the numbering in Appendix B are placed in the RPN matrices based on the consequence type, frequency number, and consequence number.

To maintain fish welfare, all of the system components must work properly, which could be registered since most of the components are represented in the RPN matrix for fish welfare in Figure 4.8. The hazardous events and their outcomes are broadly acceptable or within the ALARP risk level. Risk number 6 for the dead fish pump and 4 for the water inlet in Appendix B are closest to an unacceptable risk, and risk-reducing measures should be examined.



RPN-Matrix Fish welfare		Frequency:				
		1	2	3	4	5
Consequence:	5		Df-6			
	4		Wi-2 Wo-2,6	Wi-4		
	3			Wi-1 S-8		
	2		Wo-1	Wi-3 Wo-5	Df-5	
	1					

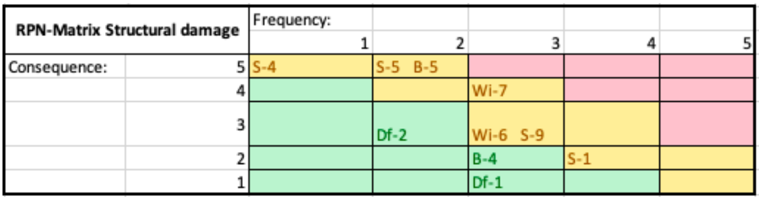
Figure 4.8: RPN-matrix for fish welfare in a semi-rigid system

The risk surrounding lice infection on the fish inside the cage is affected by hazardous events on the water inlet systems and the buoyancy/floater. The risk of lice entering through the water inlets or over the floating collar is acceptable. However, some risk-reducing measures should be considered to reduce the risk as low as reasonably possible.

RPN-Matrix Lice		Frequency:				
		1	2	3	4	5
Consequence:	5					
	4			Wi-7		
	3			B-2		
	2			Wi-5	B-1	
	1					

Figure 4.9: RPN-matrix for lice in a semi-rigid system

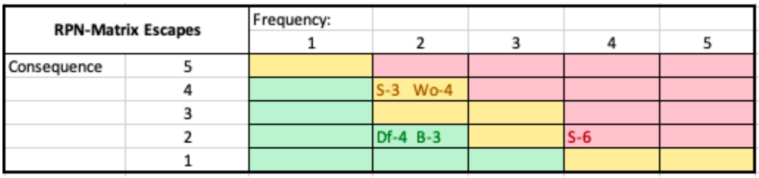
A semi-rigid S-CCS operating in moderate exposure will experience large loads from waves and currents. If the loads exceed what the structure and system components are designed for, damage and potential breakdown will arise. The risks of damage or destruction to the structure or main components are all acceptable. However, damage to the water inlet or structure due to large forces and damage to floaters caused by vessels are barely within an acceptable level, as illustrated in Figure 4.10.



RPN-Matrix Structural damage		Frequency:				
		1	2	3	4	5
Consequence:	5	S-4	S-5 B-5			
	4			Wi-7		
	3		Df-2	Wi-6 S-9		
	2			B-4	S-1	
	1			Df-1		

Figure 4.10: RPN-matrix for structural damage on a semi-rigid system

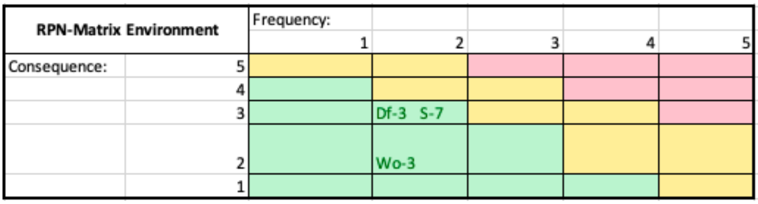
Escapes are potential outcomes if hazardous events occur on the water outlets, the structure, or the dead fish pumps. Risks of hazardous events causing escapes are considered acceptable for all events except outcome number 6 on the structure as shown in Figure 4.11. To operate with an acceptable risk, measures must be taken to reduce the risk of bad weather and rough sea causing damage to the structure. Designing for more extreme conditions and mounting a safety net as a double barrier for escapes are suggested measures.



RPN-Matrix Escapes		Frequency:				
		1	2	3	4	5
Consequence	5	🟨	🟥	🟥	🟥	🟥
	4	🟩	🟨 S-3 Wo-4	🟥	🟥	🟥
	3	🟩	🟨	🟨	🟥	🟥
	2	🟩	🟩 Df-4 B-3	🟨	🟥 S-6	🟥
	1	🟩	🟩	🟩	🟨	🟨

Figure 4.11: RPN-matrix for escapes in a semi-rigid system

Operating a semi-rigid system with moderate exposure comes with a low risk of harming the environment. As seen in Figure 4.12, all of the outcomes are well within the green area representing a broadly acceptable risk.



RPN-Matrix Environment		Frequency:				
		1	2	3	4	5
Consequence:	5	🟨	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	🟩 Df-3 S-7	🟨	🟨	🟥
	2	🟩	🟩 Wo-3	🟩	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨

Figure 4.12: RPN-matrix for environmental impact for semi-rigid systems.

4.1.3 Rigid semi-closed containment systems

The results of the preliminary hazard analysis for rigid structures operating in moderate exposure is presented in Appendix C.

Water inlet

When it comes to risk regarding fouling and blockage of the water inlet pipes for rigid systems, the risk is assumed to be relatively similar for all the systems as there is little that separates the systems at depths where water enters the inlet pipes. As for the flexible and semi-rigid S-CCSs, there is a proposed increase in inspection and maintenance of critical parts as frequency-reducing measures. For consequence measures, it is proposed to allow other pipes to increase the flow rate if one of the inlet pipes is blocked to maintain sufficient flow in the system.

Technical errors have been a repetitive hazard during testing and operating S-CCS as informed in section 2.4. Technical errors leading to a hazardous event of a water inlet pump stop. Such pump stops could have severe consequences. In past experiences, there have been registered 25% mortality of fish due to technical errors causing pump failure(Røen, 2014). The risk is relatively like for rigid cages as for the other types, but a rigid cage could provide more space for a redundant backup power supply.

What differentiates a rigid structure from flexible and semi-rigid structures regarding water inlet systems is that the structure allows for better protection of the pipes. The rigid

S-CCS Salmon Home no1 has implemented voids in the structure wall where water inlet pipes are mounted and stay protected from external forces such as waves, currents, and operating vessels(Clarke et al., 2018). This reduces the risk of damaging the water inlet pipes, mainly the frequency of hazardous events. Protecting the pipes by locating the components inside the wall of the rigid structure ensures a broadly acceptable risk regarding damage or destruction of the pipes, as seen in Appendix C.

Water outlet

Water outlets are well-protected in the rigid structure, making them relatively unaffected by forces from waves and currents. As seen in Appendix C, the main concerns for water outlets are technical errors causing disruptions to the water flow and water exchange. A sufficient water flow is essential to keep the CO2 levels at acceptable levels and to remove wastes from fish and fish feed out of the contained water. The risk of technical failures or human errors affecting the water flow is acceptable within the ALARP risk area. Redundant systems and increased maintenance of the component are suggested risk-reducing measures. Also, blockage of the outlets is a potential hazard, but with a low frequency of occurrence, the risk is broadly acceptable.

Structure/Wall

When it comes to risk regarding fouling and blockage of the water inlet pipes for rigid systems, the risk is assumed to be relatively similar for all the systems as there is little that separates the systems at depths where water enters the inlet pipes. As for the flexible and semi-rigid S-CCSs, there is a proposed increase in inspection and maintenance of critical parts as frequency-reducing measures. For consequence measures, it is proposed to allow other pipes to increase the flow rate if one of the inlet pipes is blocked to maintain sufficient flow in the system.

Technical errors have been a repetitive hazard during testing and operating S-CCS as informed in section 2.4. Technical errors that lead to a stop in the water inlet pumps are listed in Appendix C. Such pump stops could have severe consequences. In past experiences, there have been registered 25% mortality of fish due to technical errors causing pump failure(Røen, 2014). The risk is relatively like for rigid cages as for the other types, but a rigid cage could provide more space for a redundant backup power supply.

Well-boats and other operating vessels on and around the floating closed cage could potentially threaten the system. Difficult maneuvering conditions, lack of attention, and lack of training could contribute to hazardous events of a collision or powerful impacts between a vessel and the S-CCS. According to Clarke et al. (2018) there is no doubt that rigid structures can withstand larger forces compared to semi-rigid and flexible structures. As a result, the risks of causing cracks to the rigid wall and potential escapes as an outcome of the damages are considered broadly acceptable in Appendix C. However, the severity of causing destruction has such high consequence numbers that the risk falls within the ALARP area, even if the frequency is assumed to be remote. Impact dampers and better training for the crew could reduce the risk even further.

Even though Clarke et al. (2018) says that rigid structures are more capable of withstanding large forces, it might cause fatigue over time. There are some concerns surrounding semi-rigid and rigid closed containment systems. From an engineering point of view, these concerns are based on whether solid walls can withstand forces from the currents and waves over time(Chadwick et al., 2010). In moderate exposure, higher waves and currents will act on the structure and cause stress and fatigue that could potentially result in the loss of structural integrity of the system. Cracks have developed in Agrimarine's rigid structure during periods of bad weather, as stated in section 2.4. The frequencies of such hazardous events are assumed to be remote, but the consequence is severe, making it an acceptable risk, but risk-reducing measures should be proposed. The structure should be designed for more extreme weather and sea loads. In addition, mooring lines must be designed for larger stresses as the rigid S-CCS has a much larger weight than flexible and semi-rigid structures.

Specific wave periods and sea states are hazards that might initiate sloshing inside the tank of a S-CCS. Research shows that rigid systems will develop larger sloshing motions than more flexible structures (Sintef, 2018). At moderate exposure, risks of damage to the structure and reduced welfare resulting from sloshing are higher than for the more flexible alternatives. The risk is acceptable, but the structure's design should be made in context with the wave exposure of the location. Designing a structure for higher natural periods could reduce the risk.

Buoyancy and floaters

There is no floating collar for rigid structures to maintain buoyancy, but buoyancy is achieved by designing flotation chambers inside the rigid wall structure (Clarke et al., 2018). The internal buoyancy chambers are separated to ensure buoyancy if damage or cracks develops on the structure. Flotation chambers allow for housing heavy equipment and provide sufficient buoyancy for the structure to maintain freeboard. Hazardous events where the water reaches over the top of the structure bringing lice and other parasites into the production volume, is a broadly acceptable risk with relatively low frequency and low degree of severity.

Well-boats and operating vessels could potentially cause harm to the structure and following the flotation chambers. These voids make the structure more complex but provide a safety measure. The separation of chambers ensures buoyancy of the structure even if the structure takes damage from impacts with vessels. In addition, the structure provides extremely safe protection for housing critical components and equipment (Clarke et al., 2018).

Dead fish pump system

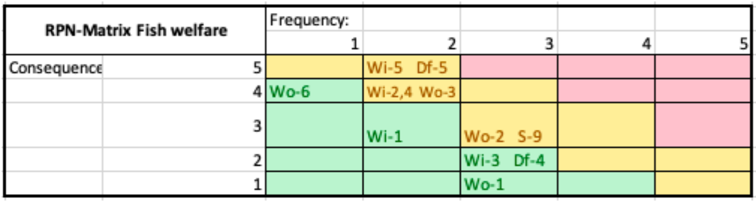
As stated earlier, the structure of rigid systems allows for secure protection of equipment and components in voids inside the rigid wall. Dead fish pumps and pipes are well protected and not exposed to waves, currents, or vessels. Therefore the risk of hazardous events caused by waves, currents, and vessels is considered improbable and broadly acceptable.

Regarding the hazardous event of technical errors causing dead fish pump system failure, there is space to implement double-installed components in case an error occurs. This will contribute to making the S-CCS more reliable during operations, resulting in a low risk that is broadly acceptable.

Risk priority number and RPN-matrices

The risks of potential outcomes due to hazards and hazardous events discussed earlier are placed in different RPN matrices based on what is affected by the event. RPN matrices for fish welfare, lice problems, structural damage, escapes, and environmental impacts are made, and the outcomes are classified as an impact on one of them.

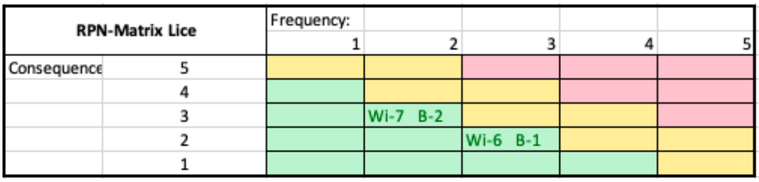
Compared to flexible and semi-rigid structures, it is a clear trend that the risk of affecting the fish welfare negatively is moving left and down in the matrix shown in Figure 4.13, which indicates that the risk mitigates. The most considerable risk regarding fish welfare in rigid structures is technical errors in the water inlet systems and the dead fish pumps. These are outcome number 5 for the water inlet component and outcome number 5 for the dead fish pump in Appendix C.



RPN-Matrix Fish welfare		Frequency:				
		1	2	3	4	5
Consequence	5	🟨	🟨 Wi-5 Df-5	🟥	🟥	🟥
	4	🟩 Wo-6	🟨 Wi-2,4 Wo-3	🟨	🟥	🟥
	3	🟩	🟩 Wi-1	🟨 Wo-2 S-9	🟨	🟥
	2	🟩	🟩	🟩 Wi-3 Df-4	🟨	🟨
	1	🟩	🟩	🟩 Wo-1	🟩	🟨

Figure 4.13: RPN-matrix for fish welfare in a rigid system.

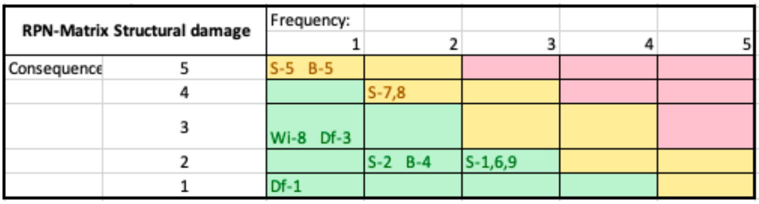
A rigid S-SSC's ability to handle the challenges of lice and lice infections on the produced fish is excellent. As seen in Figure 4.14, all events leading to lice infections are broadly acceptable, and no risk-reducing measures are necessary.



RPN-Matrix Lice		Frequency:				
		1	2	3	4	5
Consequence	5					
	4					
	3		Wi-7 B-2			
	2			Wi-6 B-1		
	1					

Figure 4.14: RPN-matrix for lice in a rigid system

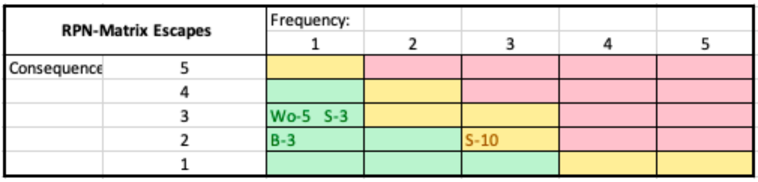
The tendency to move left and downwards in the RPN matrix for rigid systems compared to the more flexible alternatives also applies to the risk of structural damage. Most of the events leading to damage to the structure or the system's main components are within the broadly acceptable risk level. Events where large waves cause damage directly to the structure and events where operating vessels make impacts causing damage to the wall, and flotation chambers are a risk that falls within the ALARP area as shown in Figure 4.15.



RPN-Matrix Structural damage		Frequency:				
		1	2	3	4	5
Consequence	5	S-5 B-5				
	4		S-7,8			
	3	Wi-8 Df-3				
	2		S-2 B-4	S-1,6,9		
	1	Df-1				

Figure 4.15: RPN-matrix for structural damage on a rigid system

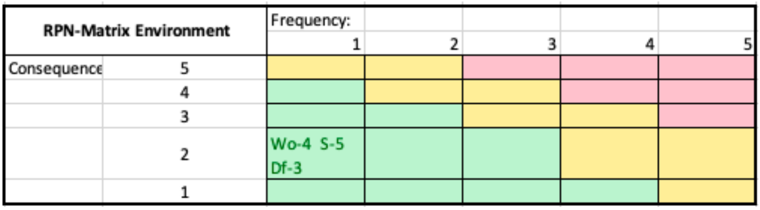
Escapes from a rigid structure are unlikely, with three outcomes well within the green area in Figure 4.16. Event S-10 in Appendix C, where sloshing causes considerable damage to the structure and escapes, is the event with the highest risk. With a frequency number of 3 and consequence severity number of 2, the risk is within the ALARP area, and risk-reducing measures should be considered.



RPN-Matrix Escapes		Frequency:				
		1	2	3	4	5
Consequence	5					
	4					
	3	Wo-5 S-3				
	2	B-3		S-10		
	1					

Figure 4.16: RPN-matrix for escapes in a rigid system.

Releases from a rigid cage harming the environment have very low risk as the structure is well suited to withstand forces, and the dead fish pump is sheltered within the structure. All events are broadly acceptable and well within the green area ass illustrated in Figure 4.17.



RPN-Matrix Environment		Frequency:				
		1	2	3	4	5
Consequence	5	🟨	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	🟩	🟨	🟨	🟥
	2	🟩 Wo-4 S-5 Df-3	🟩	🟩	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨

Figure 4.17: RPN-matrix for environmental impacts for a rigid system.

4.2 Comparative analysis

The preliminary hazard analysis identified potential hazards and hazardous events for relevant components. Several possible outcomes were investigated and given a score based on the frequency of occurrence and severity of the outcomes, which resulted in a risk priority number. The RPN indicates the extent of the risk, if it is broadly acceptable, acceptable - but should be made as low as reasonably possible or unacceptable. A comparative analysis was conducted to examine how the risk differs among the different types of S-CCS. The comparison is based on the RPN values from the PHA. All system components investigated in the PHA are compared, focusing on how they scored in the different consequence types. The consequence types are

- Fish welfare;
- Lice;
- Structural damage;
- Escapes
- Environment

Dividing the system into main system components and further categorizing the risk within different consequence types helps gain knowledge of where the hazards arise and the effect of the hazardous event. Also, it would be beneficent for handling the risk. The results of the comparative analysis are presented in the sections below.

4.2.1 Water Inlet

Water inlet pumps and pipes are crucial parts of S-CCSs as they provide high-quality water where fish can live a healthy life and grow as intended. As described in the PHA analysis, several severe hazards could be of risk to the water inlet systems. Potential outcomes of the hazards and hazardous events will affect the system, fish, or environment. The average RPN values shown in Table 4.1 indicate that the risk of affecting fish welfare, lice problems, and structural damage are relatively similar for flexible and semi-rigid structures, with a slightly higher risk for flexible cages. The structure of a semi-rigid cage can support the inlet pipes from motions caused by waves and currents. This support is non-existent in flexible bags. Rigid structures have the ability to protect the pipes down to considerable depths. Reduced motion and protection from impacts make the risk broadly accepted and significantly lower than flexible and semi-rigid systems regarding lice infections and structural damage.

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
Water Inlet	Fish welfare	6,2	6,0	5,5
	Lice	6,3	6	4,5
	Structural Damage	6,5	6,5	5
	Escapes	-	-	-
	Environment	-	-	-

Table 4.1: Comparative risk analysis of the water inlet system for the different S-CCS structures.

Hazardous events and outcomes affecting the environment and escapes for water inlet pipes are considered negligible. As seen in Table 4.1 above, there are no RPN values for escapes and environment.

4.2.2 Water Outlet

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
Water Outlet	Fish welfare	6,5	5,3	5,3
	Lice	-	-	-
	Structural Damage	-	-	-
	Escapes	5	5	4
	Environment	5	4	4

Table 4.2: Comparative risk analysis of the water outlet system for the different S-CCS structures.

4.2.3 Structure/wall

Flexible, semi-rigid and rigid structures use different materials in their enclosed wall. These materials have different properties and behavior when exposed to waves and currents. The semi-rigid and rigid structures are somewhat similar, as the structure will not deform to the same extent as flexible structures under loads. Semi-rigid structures may experience some deformation but are not susceptible to excessive deformation. Flexible structures have disadvantages as they are susceptible to severe deformation when exposed to hydrodynamic loads, which could affect fish welfare. However, a flexible bag generates less sloshing motions than the other more rigid alternatives. As seen in Table 4.3, the different systems have the same average RPN regarding fish welfare. This is a result of the increased sloshing motion of more rigid tanks, even though a flexible system could deform. The rigid system performs within the broadly acceptable risk for the remaining consequence categories as the material is more robust and components better protected.

Flexible and semi-rigid operates with a relatively similar average RPN and falls within the ALARP area for structural damage and escapes, but both are broadly acceptable regarding environmental impact.

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
Structure/closed wall	Fish welfare	6	6	6
	Lice	-	-	-
	Structural Damage	6	6	4
	Escapes	5,7	5,5	4
	Environment	5	5	4

Table 4.3: Comparative risk analysis of the structure or closed wall for the different S-CCS structures.

4.2.4 Buoyancy/ floaters

For marinating position afloat, flexible and semi-rigid containment systems use floating elements around the cage called floating collars. The floating collar must bear the weight of machinery and equipment. Rigid structures are much heavier constructions where the chambers are built inside the wall to maintain buoyancy. The chambers are separated for safety measures and could provide voids for storing and protecting necessary machinery and equipment. The remaining chambers could be filled with lightweight material to prevent water from filling. The mass of fouling and heavy equipment is low in relation to a rigid structure. For flexible and semi-rigid structures, the mass of fouling and equipment are considerable weights in relation to the structure. Reduced freeboard causing waves to break over the top, bringing lice or other parasites into the production volume, is considered a broadly acceptable risk for rigid tanks. The risk is somewhat higher within the ALARP area for the other two alternatives. Rigid structures are also capable of enduring larger forces than flexible bags and semi-rigid tanks, resulting in a lower RPN for rigid tanks, as shown in Table 4.4.

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
Buoyancy/ floaters	Fish welfare	-	-	-
	Lice	6	6	5
	Structural Damage	6	6	5
	Escapes	4	4	3
	Environment	-	-	-

Table 4.4: Comparative risk analysis of the structure or closed wall for the different S-CCS structures.

4.2.5 Dead fish pumps and pipes

Transportation of fish feed, feces, and dead fish out of the systems is a necessary process for maintaining good water quality inside the cage. For all systems, technical errors causing pump failure are the most significant risks and affect negatively affect fish welfare. As shown in Table 4.5, all types of S-CCS are within the ALARP area regarding events affecting fish welfare. For flexible and semi-rigid dead fish, pipes are mostly mounted outside the enclosed wall, exposed to waves, currents, and operating vessels. Flexible systems have a slightly higher risk of structural damage and tearing of the system as it will experience motion on the bag that can damage the cloth. Rigid systems protect the equipment, and pipes are mounted on the inside of the wall, protecting it from external loads and following low risk.

Comparative Analysis	Category\structure	Flexible	Semi-rigid	Rigid
Dead fish pump/pipes	Fish welfare	6,5	6,5	6
	Lice	-	-	-
	Structural Damage	5,3	4,7	3
	Escapes	5	4	-
	Environment	5	5	3

Table 4.5: Comparative risk analysis of dead fish handling system for the different S-CCS structures.

What is essential to address when using an average risk-based comparison analysis is that even if the average risk is within acceptable values, there might be individual risks that are unacceptable, hidden within the average score. For the component, flexible bag, of a flexible S-CCS, the comparison analysis indicates an acceptable risk within the ALARP area regarding escapes as shown in Table 4.3. However, there are two individual risks for the system component that has an unacceptable risk when it comes to escapes.

4.3 Change analysis

The thesis aims to investigate and understand how the risk changes when using the different types of S-CCS at different sites where exposure varies. The preliminary hazard analysis for moderate exposure is used as a reference point for the risk. Further, a change analysis was conducted by changing the operating S-CCS location to more and less exposed areas. The new risks are investigated as a result of changing the operating location. Both changes in frequency and consequence were looked into, and how these affect the new risk priority number. A change in risk will not be experienced for all listed hazardous events, and those who are relatively unaffected are not considered in the change analysis.

4.3.1 Change of location - Less exposed areas

In less exposed areas, there will be smaller waves and lower currents. As a result, the loads working on the system are lower. The system and its components are better suited to withstand the reduced forces. Destruction of critical system components and potential material deformation are less likely to occur in more sheltered areas.

Flexible semi-closed containment systems

From the PHA, it was clear that a flexible system has some challenges regarding the deformation of the structure and main system components. In addition, the structure is less capable of providing protection for the components and necessary equipment. Forces from waves and currents are one of the major threats to S-CCS and could potentially cause harm.

The hazardous events that could be of risk to the water inlet system were listed in the PHA. Events that will experience a change of risk caused by changing location to less exposed areas are damage or destruction of water inlet pipes due to forces from sea, weather, or vessels. The following potential outcomes are considerable damage to the water inlet pipes and cracks or destruction, causing parasites and unwanted organisms to enter the system. As seen in Table 4.6, the risk was considered acceptable, but risk-reducing measures should be considered for moderate exposure. The new risk for lower exposure reduces the frequency of occurrence, and the consequence is reduced to a broadly acceptable risk. The risk priority numbers have dropped by 33% for external forces causing considerable damage to the pipes and 29% for destruction resulting in parasites and other organisms entering the system.

What is essential to address when using an average risk-based comparison analysis is that even if the average risk is within acceptable values, there might be individual risks that are unacceptable, hidden within the average score. For the component, flexible bag, of a flexible S-CCS, the comparison analysis indicates an acceptable risk within the ALARP area regarding escapes as shown in Table 4.3. However, there are two individual risks for the system component that has an unacceptable risk when it comes to escapes.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Weather/sea, operating vessels and lice	Damage or destruction on water inlet pipes due to forces from bad weather/sea or contact between operating vessel and inlet pipe.	Considerable damage to water inlet pipes	3	3	6	2	2	4	-33%
			Water from upper layer of the sea enters the system due to cracks or destruction of pipes, resulting in possible lice problems.	3	4	7	2	3	5	-29%

Table 4.6: Change analysis of the water inlets on a flexible system when moving from moderate exposure to less exposed areas.

Technical errors or other failures in the water outlet will affect the water exchange and water flow inside the system. A pressure drop could arise inside the cage caused by failures with the water outlet components leading to deformations of the bag. Deformations will disrupt the self-cleaning ability of the system and increase the drag force of the system due to the parachute-like form of the bag. The risk of disrupted self-cleaning ability for moderate exposure was within the ALARP levels. These effects are less significant when moving to less exposed areas due to minor deformations. The risk priority number decreases 33% from 6 to a broadly acceptable risk of 4. Regarding increased drag forces due to deformations, these forces are dependent on the current velocity. Therefore the risk is mitigated at low exposure sites where the current velocities and waves are smaller. The decrease of RPN is 40% by moving from moderate exposure sites to low exposure sites.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Technical error, loss of control	Loss of overpressure causing reduced change of water through water outlet.	Reduced pressure inside the bag leading to reduced volume, disrupting self-cleaning ability and reducing fish welfare.	3	3	6	2	2	4	-33%
			Reduced pressure leading to increased drag force and fatigue on mooring system	3	2	5	2	1	3	-40%

Table 4.7: Change analysis for water outlets on a flexible system when moving from moderate exposure to less exposed areas.

The system component for a flexible S-CCS that is most affected by a change of site is the flexible bag enclosing the system. When operating in waves and currents, the bag will experience motion due to the negligible bending stiffness of the material. Larger waves with specific periods will excite the system, and a wave-like motion of the bag will occur. Damages to the bag could be either directly from the motion because of snap loads or by motion close to equipment with sharp edges, such as the dead fish pump. Outcomes include loss of structural integrity with the need for repairs and, worst case, a large number of escapes. Significant wave heights are lower for low-exposure sites, reducing the bag's motion. A stationary bag contributes to mitigating the risk of structural damage and escapes to broadly acceptable risk, as shown in Table 4.8.

Incoming waves with frequencies close to the natural sloshing periods will develop internal waves inside the bag. If sloshing is allowed to grow, it will cause fatigue and stress for the bag, resulting in damage over time. At moderate exposure, larger waves with higher wave periods are more likely to excite the S-CCS with periods close to the natural sloshing periods. By changing location to low exposure, significant wave height decreases, and smaller wave periods will have fewer resonance problems for the structure. The new risk for the flexible bag is broadly accepted, as shown in Table 4.8.

System component	Moderate exposure			Old risk			New risk			Change of risk (%)
	Hazard/threat	Hazardous event	Initial consequence	Frequency	Consequence	RPN	Frequency	Consequence	RPN	
Flexible bag	Motion and sharp edges on dead fish pump and water outlets	Damage on material close to the sludge/dead fish pump/pipe due to motion of the pipe and the flexible bag.	Severe rift in bag, leadin to large amount of escapes (150 000 <X <500 000)	2	4	6	1	3	4	-33 %
	Certain sea states and wave periods. Resonance	Material damage in the bag material due to snap loads.	Loss of structural integrity of the system. Change of cloth is required	2	5	7	1	3	4	-29 %
			Large amounts of escapes	2	4	6	1	3	4	-17 %
	Large waves	Waves with certain periods causing sloshing inside the tank.	Damage and fatigue on the flexible fabric/structure.	3	3	6	2	3	5	
			Stress and harmful environment for fish to live in. Injuries and increased mortality will occur.	3	3	6	2	2	4	-33 %

Table 4.8: Change analysis for the flexible bag of a flexible system when moving from moderate exposure to less exposed areas.

For the system to stay afloat, sufficient buoyancy from floaters is necessary. The floaters must carry the structure's weight, system components, and equipment. Also, fouling could add significant mass to the S-CCS. Extra mass due to fouling will reduce the freeboard. In combination with large wave amplitudes, lower freeboard causes a threat of untreated water reaching over the top of the floater, bringing parasites and unwanted organisms with it. Lower waves at less exposed areas reduce the RPN by 33%, making it a broadly acceptable risk for the new operating site as shown in Table 4.9. This is an acceptable risk at low exposure, but measures should be taken.

The floaters will experience significant impacts from operating vessels due to difficult maneuvering conditions at moderate exposure sites where the maneuvering conditions are more challenging. Less current and smaller waves will ensure easier maneuvering conditions and a safer operation—a risk reduction of 17% results from changing to more sheltered areas. There could still be significant power impacts, but the frequency of occurrence is reduced.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Buoyancy and floaters	Heavy equipment, Waves and fouling	Untreated water entering the system over the floating collar due to waves and to low freeboard.	Lice and pathogens problem causing several treatments and diseases among the stock	3	3	6	2	2	4	-33%
	Well boats or other operating vessels	Collision or powerful impacts between operating vessel and S-CCS.	Severe damage to floaters resulting in loss of buoyancy and destruction of main parts of the system	2	4	6	1	4	5	-17%

Table 4.9: Change analysis for floaters and buoyancy of a flexible system when moving from moderate exposure to less exposed areas.

As stated in the PHA, a flexible cage cannot protect dead fish pumps and pipes in the structure. The dead fish pump system is mounted at the bottom of the bag, with the following pipes mounted outside the bag. As a result, the dead fish system is exposed to forces from the sea and potential contact with operating vessels. Reducing forces from hydrodynamic loads and impacts will reduce the frequency and mainly cause minor damage to the system. Clogged pipes due to significant deformations of the dead fish pipes are within the ALARP area for moderate exposure. The risk is reduced for lower currents and waves to a broadly acceptable risk.

In the worst case, the dead fish pump could be torn off if the forces acting on the components are large enough. Since these forces are reduced drastically for low exposure sites, the frequency is lower, and it will be experienced wear on the material instead of a torn-off pipe. The result is a 40% decrease of the RPN, which could be seen in Table 4.10.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Dead fish pump/ pipe	Current & waves or vessels	*Loads from waves and current acting on the dead fish pump and pipe. *Vessels operating near the dead fish pipe makes contact with the pipe.	Clogged pipes due to larger deformations on pipe. Accumulation of sludge in the system.	3	3	6	2	2	4	-33%
			Torn off dead fish pipe, causing escapes and release of sludge	2	3	5	1	2	3	-40%

Table 4.10: Change analysis for dead fish system on a flexible system when moving from moderate exposure to less exposed areas.

Semi-Rigid Semi-Closed Containment Systems

In moderate exposures investigated in the PHA, it was observed that a semi-rigid structure would experience loads that could cause harm to system components. Also, some deformations of the structure will occur due to the lower bending stiffness compared to a rigid cage. The deformations are connected to the hydrodynamic loads from waves and currents.

Like for flexible cages, a semi-rigid system will have a low ability to protect the water inlet pipes. High waves, strong currents, and impacts between vessels and the system will act on the pipes and potentially cause damage to the components. Risks of these loads causing considerable damage or destruction to the pipes, making a free entrance for lice and other unwanted organisms, are acceptable for moderate exposure but still relatively high. Table 4.11 shows how the frequency and consequence changes reduce. The risk of hazards causing considerable damage to the pipes with the need for repair and maintenance is reduced by 33%, while cracks or destruction leading to lice, parasites, and organisms entering the system is reduced by 43% when operating in low exposure.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Weather, rough sea and vessels. In addition, lice	Weather and sea causing large loads on water inlet pipe and causing damage on the system.	Considerable damage to water inlet pipe causing need for repair and maintenance	3	3	6	2	2	4	-33%
			Severe damage on pipe causing water from upper layer of the sea enters the system resulting in lice entering the system.	3	4	7	2	2	4	-43%

Table 4.11: Change analysis for water inlet systems on a semi-rigid structure when moving from moderate exposure to less exposed areas.

Loads from currents and rough seas will act on the water outlets. Filtration systems or technical functions will take damage over time due to loads from the sea. Damage to the water outlet components will result in hazardous events if the damage is severe enough. Events might lead to sludge being released into the environment, or fish could escape. Damage to the system mostly depends on the hydrodynamic forces, mainly from currents. However, the risk is low at moderate exposure and will decrease at low exposure sites, as shown in Table 4.12. The frequency of damage-causing release of sludge is reduced, but the consequence of releasing sludge at these sites is that the currents have a reduced ability to spread the sludge. The impact on the local seabed will be higher at low-exposure sites.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Bad weather/ rough sea.	Fatigue, wear and tear or damage on filtration systems at the water outlet.	Release of fish feces and feed (sludge) to the local environment.	2	2	4	1	3	4	-0%
			Escapes of fish	2	3	5	1	3	5	-20%

Table 4.12: Change analysis for water outlet of a semi-rigid system when moving from moderate exposure to less exposed areas.

Large waves and certain wave periods will excite the water inside the tank an cause sloshing. Sloshing is development of internal waves inside the closed cage that occurs when incoming waves with frequencies close to the natural sloshing period. At moderate exposure, larger waves and wave periods are more likely to excite the water inside the tank. Operating at less exposed sites will mitigate the risk of causing harm to the fish or the structure. The frequency and severity of sloshing is reduced with a total RPN reduction of 33% for both outcomes reducing the fish welfare and considerable damage to the structure as shown in Table 4.13. The new risk is broadly acceptable.

Incoming waves does not only initiate sloshing, it will also cause directly loads on the structure with severe outcomes if the hydrodynamic loads are large enough. Structural collapse as a result of rough sea and storms have been experienced in the past. More sheltered areas will protect the structure increasingly from rough sea. Structural collapse and loss of structural integrity leading to escapes are outcomes where the risk decreases due to change of location. At moderate exposure structural collapse was within the ALARP area, and destruction leading to escapes were an unacceptable risk for moderate exposure as seen in Table 4.13. By changing operating conditions, the risks reduces by 29% and 17% for the two outcomes.

The new site will also improve maneuvering conditions for operating vessels close to the cage. The risk of significant power impacts between vessels and S-CCSs was already broadly acceptable, but the risk is further mitigated as the frequency of such impacts reduces.

System component	Moderate exposure			Old risk			New risk			Change of risk (%)
	Hazard/threat	Hazardous event	Initial consequence	Frequency	Consequence	RPN	Frequency	Consequence	RPN	
Structure/ closed wall	Waves and wave periods	Waves with certain periods causing sloshing inside the tank.	Stress and harmful environment for fish to live in.	3	3	6	2	2	4	-33 %
			Considerable damage on structure	3	3	6	2	2	4	-33 %
	Bad weather and rough sea	Loss of structural integrity of the S-CCS due to damage caused by wind and waves.	Structural collapse	2	5	7	1	4	5	-29 %
			Structural damage leading to escapes of fish	2	4	6	1	4	5	-17 %
	Well boats or other operating vessels	Powerful impact between well boat and S-CCS.	Structural damage leading to holes in structure and escapes.	2	3	5	1	3	4	-20 %

Table 4.13: Change analysis for structure/wall of a semi-rigid system when moving from moderate exposure to less exposed areas.

Lower significant wave heights at the new location will reduce the risk of untreated water entering the system over the floating collar. At moderate exposure, the risk is acceptable but within the ALARP area. Moving to more sheltered areas with lower significant wave heights reduces the risk of water containing parasites, pathogens, and organisms reaching over the floaters. The new risk falls 33% and to a broadly acceptable level as seen in Table 4.14.

The changed location will ensure safer operating conditions for vessels and benefit from the risk of causing severe damage to floaters due to collision. More manageable maneuvering condition reduces the frequency of severe impacts between operating vessels and S-CCS. As seen in Table 4.14, the risk reduces by 17%.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Floater/ buoyancy	Heavy equipment/ fouling and waves	Heavy equipment/ fouling and waves	Clogged pipes due to larger deformations on pipe	3	3	6	2	2	3	-33%
	Operating vessels	Loss of control over operating vessel leading to large impacts between vessel and S-CCS.	Severe damage to floaters resulting in loss of buoyancy and severe damage of system	2	4	6	1	4	5	-17%

Table 4.14: Change analysis for floaters/buoyancy on a semi-rigid system when moving from moderate exposure to less exposed areas.

For most semi-rigid systems, dead fish pipes are placed outside the cage. The pipes are exposed to hazards such as strong currents, large wave forces, and impacts between vessels and the cage as the structure provide little protection. For lower exposure, forces from waves and currents are reduced, and contact with vessels is less likely due to easier maneuvering conditions. As a result, the risk of damage to the dead fish pump system is reduced and considered broadly acceptable at the changed site.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Dead fish pump	Current & waves or vessels	-Loads from waves and current acting on the dead fish pump and pipe. -Vessels operating near the dead fish pipe.	Clogged pipes due to larger deformations on pipe	2	3	5	1	2	3	-40%
			Torn off dead fish pipe, causing escapes and release of sludge	2	3	5	1	3	4	-20%

Table 4.15: Change analysis for dead fish pump and pipe on a semi-rigid system when moving from moderate exposure to less exposed areas.

Rigid semi-closed containment systems

Unlike flexible and semi-rigid structures, a rigid structure will have no deformations due to the high bending stiffness. The material is increasingly designed to withstand large forces as the strength of the material used in a rigid structure is higher. However, there are increasing challenges regarding the development of internal waves when exposed to waves and wave periods.

The rigid structure provides protection for the water inlet pump and pipe through voids inside the wall. The risk of waves and currents causing damage or destruction to the pipes is already low for moderate exposure and broadly acceptable. The probability of cracks or destruction of water inlet pipes leading to lice, pathogens, and organisms entering the system is extremely rare at moderate exposure. The risk reduces even further when changing to less exposed sites due to smaller waves and currents acting on the system. The risks are almost negligible as shown in Table 4.16 below.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Strong weather and rough sea	Storm, strong wind, large waves and strong current acting on the inlet pipes and S-CCS.	Minor damage on water inlet pipes	2	3	5	1	2	3	-40%
			Water from upper layer of the sea enters the system resulting in lice problems.	1	3	4	1	2	3	-25%

Table 4.16: Change analysis for water inlet on a rigid system when moving from moderate exposure to less exposed areas.

Hydrodynamic loads will act on the water outlets. Over time fatigue and wear on the water outlet affects the filtration of wastes in the form of fish feces and leftover feed. At moderate exposure, stronger currents will act on the water outlets than in low-exposure sites. The frequency of damage to the filtration system inside the water outlets is lower for less exposed areas, reducing the potential release of sludge to the environment. However, the site's ability to spread the released particles decreases as the currents decreases. In Table 4.17, the risk change indicates that the consequence is the same, while the RPN is reduced by 25%.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Bad weather/ sea, Wear and tear	Damage/ failure on filtration systems	Release of fish feces and feed(sludge) to the local environment.	2	2	4	1	2	3	-25%

Table 4.17: Change analysis for water outlet on a rigid system when moving from moderate exposure to less exposed areas.

Forces from waves will act directly on the main structure and cause stress and fatigue to the material. Over time these forces could lead to the loss of structural integrity of the rigid cage. The magnitude of these forces is dependent on the current velocity and wave heights. Moving to less exposed areas will reduce the risk of losing structural integrity from the ALARP area to a broadly acceptable risk level, as shown in Table 4.18.

Incoming waves with certain wave periods will also cause sloshing inside the cage if the wave period is close to the natural sloshing period. As stated in the PHA, rigid cages are more capable of developing large sloshing motions inside the tank. These motions will eventually cause stress on the structure and potentially damage it. In addition, fish could be harmed by internal waves, which eventually result in mortality. At low exposure sites, the waves and periods are smaller, making the risk of significant sloshing motion an acceptable risk, as shown in Table 4.18. Mitigating the sloshing motions will help maintain fish welfare and structural integrity.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Structure/wall	Well boats and operating vessels	Powerful impact between wellboat and S-CCS.	Loss of structural integrity leading to a large number of escapes.	2	3	4	1	2	3	-25%
	Weather and rough sea	Large loads from large waves and strong wind acting on the rigid cage.	Loss of structural integrity on the main structure of the S-CCS.	2	4	6	1	4	5	-17%
	Large waves and certain wave periods	Waves with certain periods close to the sloshing natural period causing sloshing inside the tank.	Stress and harmful environment for fish to live in. It will cause injuries and increased mortality.	3	3	6	2	2	4	-33%
			Considerable damage on structure	3	3	6	2	2	4	-33%

Table 4.18: Change analysis for structure/wall of a rigid system when moving from moderate exposure to less exposed areas.

A rigid system does not have a floating collar to stay afloat. The buoyancy is obtained through chambers and voids in the structure. Potential hazards of heavy equipment and fouling are causing reduced freeboard does not affect the rigid structure as much as flexible and semi-rigid structures as the weight is relatively low compared to the structure. A low freeboard allowing waves and parasites to enter the system over the top of the structure at moderate exposure is a broadly acceptable risk. In areas with lower significant wave heights, the risk is even less with a 40% lower RPN number which is illustrated in Table 4.19.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Buoyancy/floaters	Heavy equipment/ fouling and waves	Untreated water entering the system over the floating collar	Lice problem causing severeal treatments	2	3	5	1	2	3	-40%
	Well boats or other vessels	Collision or powerful interaction with vessel and S-CCS.	Severe damage to floaters resulting in loss of buoyancy and total damage of system	1	5	6	1	4	5	-17%

Table 4.19: Change analysis for buoyancy/floaters on a rigid system when moving from moderate exposure to less exposed areas.

4.3.2 Change of location - More exposed areas

As of today, most of the operating floating, semi-closed containment systems operate at low-exposure sites. There are still immense challenges with operating at sites with higher significant wave heights due to sloshing and enormous forces acting on the structures and system components.

Flexible Semi-Closed Containment Systems

In more exposed areas, a flexible cage will face several problems. More significant deformations and damage to critical components are more likely to occur when changing locations with higher significant wave heights and stronger currents. The probability of severe outcomes such as structural damage and escapes is much higher.

The water inlet pipes will experience large drag forces from the entire structure's waves, currents, and motion. Fractures on inlet pipes have happened at far less exposed sites, and by moving to areas with increasing forces, the hazardous events of causing harm are more probable. In Table 4.20, it could be seen that the initial risk for considerable damage to the pipes increases by 50% to an unacceptable risk. Increasing loads will cause more severe damage to the pipes as well as the occurrence is more rapid. In the worst case, the pipes break off, allowing parasites and organisms to enter the system.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Weather/sea, operating vessels and lice	Damage or destruction on water inlet pipes due to forces from bad weather/sea or impact between operating vessel and inle pipe.	Considerable damage to water inlet pipes	3	3	6	4	5	9	50%
			Water from upper layer of the sea enters the system resulting in possible lice problems.	3	4	7	4	5	9	29%

Table 4.20: Change analysis for water inlet on a flexible system when moving from moderate exposure to more exposed areas.

The flexible structure does not protect the water outlets located on the bag. Moving more exposed will result in more enormous stresses and, over time, fatigue on the outlet system. Control of water exchange is critical for the bag to maintain its shape. Failures on the water outlet could result in loss of overpressure inside the bag. This will have severe consequences for the S-CCS, especially in exposed areas. The wave forces and strong currents will deform the bag, reducing the volume for fish to move freely and disrupting the system's self-cleaning ability. As presented in Table 4.21, the initial risk is acceptable within the ALARP area. Moving more exposed affects the risk a lot. The hazardous events will occur more rapidly with more severe outcomes. The change of RPN is an increase of 50%, and not acceptable.

Deformations will also affect the drag forces on the system. Parachute-like form of the bag will develop, which will multiply the drag forces several times. Larger drag forces exceeding the designed loads of the mooring lines will cause fatigue and could cause the mooring lines to snap. The frequency is relatively low, resulting in an acceptable risk within the ALARP area.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Fatigue, wear and tear	Loss of overpressure causing reduced change of water through water outlet.	Reduced pressure inside the bag leading to reduced volume, disrupting self-cleaning ability and reducing fish welfare.	3	3	6	4	5	9	50%
			Reduced pressure leading to increased drag force and fatigue on mooring system	3	2	5	3	4	7	40%

Table 4.21: Change analysis for water outlet on a flexible system when moving from moderate exposure to more exposed areas.

The motion of the bag will develop when operating in waves and currents. These motions will be larger in more exposed areas, potentially hazardous to the flexible bag. Motions close to the dead fish pump and water outlet where there are components with sharp edges will cause wear and tear on the cloth, which could result in the fabric tearing and a large amount of fish escaping. Since the fabric has negligible bending stiffness, operating in more exposed areas will be crucial. The frequency of occurrence increases, and the consequence will be more severe as the rift will be teared up, increasing the number of escapes. From the initial risk, an increase of 50% will occur by moving to more exposed sites, where the risk is unacceptable.

Certain wave periods will excite wave-like motions in the bag propagating towards the bottom. These motions will if large enough, cause large snap loads on the bag. Snap loads will cause strain on the material and, for severe outcomes, loss of structural integrity of the bag. By moving to more exposed sites, the magnitude of snap loads has more severe outcomes with a higher frequency. Tearing the bag is more probable, with many fish escaping. For the new site, the risk is unacceptable with an RPN of 9, as shown in Table 4.22.

Higher waves and wave periods increase the risk of large sloshing motions developing inside the bag. Exciting the water inside the bag will affect the fish, causing harm and, over time, mortality. The risk is completely unacceptable regarding fish welfare, with a 67% increase in the RPN. Further, these motions will damage and fatigue the material, which will mitigate the structural integrity. For the new site, the risk change is unacceptable, unlike moderate exposure, which is acceptable within the ALARP area.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Flexible bag	Motion and sharp edges on dead fish pump	Damage on material close to the sludge/dead fish pump.	Severe rift in bag leading to large amount of escapes (150 000 <X <500 000)	2	4	5	3	5	8	33%
	Certain sea states and wave periods.	Material damage in the bag material due to snap loads.	Loss of structural integrity of the system. Change of cloth is required	2	4	6	4	5	9	50%
			Large amounts of escapes	2	4	6	4	5	9	50%
	Large waves and certain wave periods	Waves with certain periods causing sloshing inside the bag.	Stress and harmful environment for fish to live in. Will cause injuries and increased mortality.	3	3	6	5	5	10	67%
			Damage and fatigue on the flexible fabric/structure.	3	3	6	4	4	8	33%

Table 4.22: Change analysis for flexible bag of a flexible system at more exposed areas.

The floaters have two hazards that are affected by the change. Water entering over the floating collar bringing parasites, pathogens, and organisms with it, has a higher frequency as the top of the waves could reach over the floating collar. However, the number of lice and harmful pathogens is low compared to an open-net pen. The severity of the outcomes is relatively low, leading to acceptable risks, but risk-reducing measures should be taken into consideration.

Well-boats and operating vessels also threaten the floating collar as difficult maneuvering conditions affect the vessels' control. As demonstrated in Table 4.23 slightly advance in frequency is the result, but an escalation of the collision's severity is not very probable. The risk of operating vessels causing severe damage to the floater due to large waves and strong currents are acceptable but requires risk-reducing measures.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Buoyancy and floaters	Heavy equipment, fouling and waves	Untreated water entering the system over the floating collar due to waves and to low freeboard.	Lice and pathogens problem causing several treatments and diseases among the stock	3	3	6	4	3	7	17%
	Well boats or other vessels	Collision or powerful impacts between vessel and S-CCS.	Severe damage to floaters resulting in loss of buoyancy and destruction of main parts of the system	2	3	5	3	4	7	17%

Table 4.23: Change analysis for floaters/buoyancy on flexible systems when moving from moderate exposure to more exposed areas.

The dead fish pump system is vulnerable to higher significant wave heights and stronger currents. Increasing drag forces and motions at the site will work on the system component. More considerable damage and deformations on the pipe will reduce the efficiency of the pump system. It will affect the water quality inside the production volume and calls for repair quickly before water quality drops and harms the fish. The risk is still considered acceptable, but a slight increase of 17%.

The risk of large hydrodynamic loads on the pipe system could cause the entire system to be torn off from the bag leading to large amounts of escapes. The rougher sea makes this a more probable event, and the tearing of the bag will cause large amounts of escapes. A risk increase of 40%, as shown in Table 4.24, is the result of operating in large exposure sites.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Dead fish pump system	Current & waves or vessels	-Loads from waves and current acting on the dead fish pump and pipe. -Vessels operating near the dead fish pipe makes contact with the pipe.	Clogged pipes due to larger deformations on pipe. Accumulation of sludge in the systeem.	3	3	6	4	3	7	17%
			Torn off dead fish pipe, causing escapes and release of sludge	2	3	5	3	4	7	40%

Table 4.24: Change analysis for dead fish pump system on a flexible system when moving from moderate exposure to more exposed areas.

Semi-rigid semi-closed containment systems

Hydrodynamic loads on the semi-rigid structure and its components pose a risk when producing in the S-CCS. Semi-rigid systems will have severe challenges when operating at high-exposure sites. Increased loads from waves and currents threaten components and the structure. High wave exposure enlarges the risk of deformations, even for a semi-rigid structure. These deformations will damage the structure and the critical equipment mounted on the cage. The structure provides little protection for critical components like water inlet pipes, water outlets, and dead fish pump systems.

Moving the operation facility to more exposed areas threatens the water inlet pipes as they are unprotected from large hydrodynamic loads. The semi-rigid cage lacks the structural ability to protect the pipes fully, but support to reduce the motion is possible. In moderate exposure, the pipes are better suited to endure the hydrodynamic forces, whereas, at high exposure, these forces will cause strains on the pipes and eventually considerable damage. Cracks or broken off pipes are potential outcomes. It opens for parasites, pathogens, and organisms to enter the system due to the reduced depth of the inlet water. A change of location affects the risk negatively, with RPN ending up as an unacceptable risk with considerable increase as demonstrated in Table 4.25.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Weather, rough sea and vessels. In addition parasites, pathogens and organisms.	Weather and sea causing large loads on water inlet pipe and difficult maneuvering conditions for vessels.	Considerable damage to water inlet pipe causing need for repair and maintenance	3	3	6	4	4	8	33%
			Severe damage on pipe causing water from upper layer of the sea enters the system resulting in lice entering the system.	3	4	7	4	5	9	29%

Table 4.25: Change analysis for water inlet system on a semi-rigid system when moving from moderate exposure to more exposed areas.

Damage with severe outcomes on the water outlet is less likely as the water outlets are located close to the bottom of the structure. At the lower part of the structure, wave forces are less significant, and the components are more protected from the largest wave forces close to the surface. Strong currents and motion of the body will still cause fatigue in the water outlets and the filtration systems within the outlets. If filtration is damaged, releases of sludge to the environment will occur. For more exposed areas, the probability of such events is higher, leading to a 25% increase of the RPN as shown in Table 4.26. For more severe outcomes where the damage to the outlets enables the possibility of escapes, the risk increases by 40%. Both hazardous events are classified as acceptable risks with the need for risk-reducing measures.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Rough sea, strong currents.	Fatigue, wear and tear or damage on filtration systems at the water outlet.	Release of fish feces and feed(sludge) to the local environment.	2	2	4	3	2	5	25%
			Sever damage causing escapes	2	3	5	3	4	7	40%

Table 4.26: Change analysis for water outlet of a semi-rigid system when moving from moderate exposure to higher exposure.

At high exposure, the risk of sloshing motions inside the structure increase. Both the frequency and magnitude of these motions are affected by the change in operating at more exposed areas where higher waves and wave periods occur. In moderate exposure, the risk of causing harm to fish or damaging the structure or system parts is already within the ALARP area. Operating in more giant waves with higher periods changes the risk drastically. The probability of large sloshing motions inside the cage injuring the fish and potentially killing large amounts of the batch is not accepted. Moreover, the sloshing motion will cause significant stressors on the material that, over time, leads to considerable damage. Moving the operational site increases the RPN regarding structural damage by 33%. The change of risk involving sloshing is seen in Table 4.27.

Incoming waves are also a direct hazard to the structure as they contain high energy and transfer large forces to the cage. The ability to withstand the magnitude of these forces is lower for the structure at an exposed site. Probabilities of structural collapse and large amounts of escapes are significantly heightened. The changed RPNs increase by 29% and 50% for events leading to structural collapse and destruction leading to large amounts of escapes as illustrated in Table 4.27 below.

Vessels working on and around the S-CCS will be affected by larger waves and stronger currents. Maintaining control of the vessel is more difficult at these sites as there are rough conditions. The frequency of significant power impacts causing structural damage and escapes has a slightly higher probability of occurrence. However, the risk is still acceptable within the ALARP area.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Structure/wall	Well boats or other operating vessels	Powerful impact between wellboat and S-CCS.	Structural damage leading to a large number of escapes.	2	3	5	3	3	6	20%
	Strong wind and rough sea	Loss of structural integrity of the S-CCS due to damage caused by wind and waves.	Structural collapse	2	5	7	4	5	9	29%
			Structural damage leading to escapes of fish	2	4	6	4	5	9	50%
	Waves and certain wave periods	Waves with certain periods causing sloshing inside the tank.	Stress and harmful environment for fish to live in. Will cause injuries and increased mortality.	3	3	6	4	5	9	50%
			Considerable damage on structure	3	3	6	4	4	8	33%

Table 4.27: Change analysis for structure of a semi-rigid system when moving from moderate exposure to higher exposure.

The risk regarding the floating collar is relatively unchanged. The probability of waves containing lice, bacteria, and organisms reaching over the top of the floating collar is higher due to larger wave heights. However, the consequence is of relatively low severity. The total increase of RPN is 17% and still within the acceptable risk.

Hazardous events of collision between operating vessels and the cage causing damage to the floating collar and loss of buoyancy have a severe outcome and remain unchanged. Nevertheless, the frequency number gains a value from 2 to 3, making the total RPN change 14% higher.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Floater/ buoyancy	Heavy equipment/ fouling and waves	Untreated water entering the system over the floating collar	Lice problem causing severeal treatments	3	3	6	4	3	7	17%
	Well boats and other operating vessels.	Severe damage to floaters resulting in loss of buoyancy and total damage of system	Severe damage to floaters resulting in loss of buoyancy and total damage of system	2	5	7	3	5	8	14%

Table 4.28: Change analysis for floater/buoyancy of a semi-rigid system when moving from moderate exposure to higher exposure.

The dead fish pump will experience less motion in the semi-rigid structure compared to a flexible structure as the material has a higher stiffness. However, the pipes are mounted outside the tank, making them vulnerable to damage due to currents, waves, and operating vessels. The risk is significantly higher at locations with increased wave heights and stronger currents. Risk priority numbers of more significant damages clogging the dead fish pipe increase by 40%, but still an acceptable risk. At the same time, the risk of forces tearing off the dead fish system increases by 50% from a broadly acceptable risk to an acceptable risk where risk-reducing measures should be suggested. The frequency, severity, and RPN change are listed below in Table 4.29.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Dead fish pump	Current & waves or vessels	-Loads from waves and current acting on the dead fish pump and pipe. -Vessels operating near the dead fish pipe.	Clogged pipes due to larger deformations on pipe	2	3	5	3	4	7	40%
			Torn off dead fish pipe, causing escapes and release of sludge	2	2	4	3	3	6	50%

Table 4.29: Change analysis for dead fish pump on a semi-rigid system when moving from moderate exposure to higher exposure.

Rigid semi-closed containment systems

A rigid structure is more capable of resisting forces from the sea as the strength of the material is higher. The structure also provides better protection for critical components by implementing the components in voids within the wall. The main problem of rigid structures is that the sloshing motions of the liquid are more severe than for the more flexible alternatives. Sites with higher significant wave heights will excite the sloshing motion and increase the forces acting on the structure. The sloshing motion will cause injuries and mortalities to the batch within the structure.

As stated, the water inlet pipes are mounted inside the wall. The risk of waves and currents causing damage to the water inlet pipes is, therefore, low. Operating in higher significant wave heights and current velocities will not affect the component too much, but more significant motions of the structure will be experienced. At the bottom of the water inlet pipes, larger drag forces are acting on the components. The risk of operating at these sites is higher than those with calmer seas. Nevertheless, it is considered an acceptable risk, but risk-reducing measures should be considered. The change of risk is illustrated in Table 4.30.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water inlet	Strong wind and rough sea	Storm, bad weather, large waves, strong current acting on the inlet pipes.	Minor damage on water inlet pipes	2	3	5	3	3	6	20%
			Water from upper layer of the sea enters the system resulting in lice problems.	1	3	4	3	3	6	50%

Table 4.30: Change analysis for water inlet of a rigid system when moving from moderate exposure to higher exposure.

Same as for the water inlet, water outlet components are well-protected by the structure. Damage to the filtration system within the outlets will increase in frequency. However, the release of sludge will not affect the local environment to the same degree as for lower exposure sites. More exposed areas spread the release of sludge to broader areas, mitigating the impact on the local seabed.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Water outlet	Bad weather/ sea. Wear and tear	Damage/ failure on filtration systems	Release of fish feces and feed(sludge) to the local environment.	2	2	4	3	2	5	25%

Table 4.31: Change analysis for water outlet of a rigid system when moving from moderate exposure to higher exposure.

Large power impacts between vessels and the rigid cage are more likely at higher exposure sites due to the maneuvering conditions. The rigid structure is capable of enduring large forces. The probability of impacts causing considerable damage to the structure and leading to escapes is relatively low, but the operating conditions increase the frequency. As seen in Table 4.32, a 50% increase of the RPN results from moving more exposed.

Higher waves will make a direct threat to the structure. Over time the structure will wear out. Moving to more exposed sites, damage to the structure from waves is more probable, and the frequency number increases from two to four. The increased frequency of waves causing damage to the structure and potentially loss of structural integrity is an acceptable risk at high exposure sites but just beneath the unacceptable area. Risk-reducing measures should be considered implemented.

The main challenge of operating in large waves is internal waves developing, causing large sloshing motions. Sloshing will increase both in frequency and magnitude as the incoming waves are closer to the natural sloshing period. The environment inside the cage is unbearable for fish. Many injuries and a high mortality rate are probable outcomes of moving more exposed. The risk is strongly unacceptable with a 67% increase of the RPN number as shown in Table 4.32.

Over time sloshing will cause harm to not only the fish but also the structure. The enlarged sloshing motion will, over time, impact the structural integrity and severely damage the structure and its components. RPN will increase 33% from the moderate exposure when changing location to high exposure sites. The new risk is not acceptable.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Structure/wall	Well boats and operating vessels	Powerful impact between wellboat and S-CCS.	Considerable damage to the structure, causing escapes.	1	3	4	3	3	6	50%
	Weather and rough sea	Damaging loads from large waves and strong wind acting on the rigid cage.	Loss of structural integrity on the main structure of the S-CCS.	2	4	6	4	4	8	33%
	Large waves and certain wave periods	Waves with certain periods close to the sloshing natural period causing sloshing inside the tank.	Stress and harmful environment for fish to live in. It could cause injuries and possibly mortality.	3	3	6	5	5	10	67%
			Considerable damage on the structure.	3	3	6	4	4	8	33%

Table 4.32: Change analysis for structure/wall of a rigid system when moving from moderate exposure to higher exposure.

The probability of water containing parasites and pathogens entering over the top of the system due to large waves and low freeboard is similar to a semi-rigid structure. The frequency is heightened, resulting in a 40% increase of the RPN as shown in Table 4.33. The risk is still considered acceptable, and risk-reducing measures, as motioned in the PHA, should be evaluated.

Powerful impacts between vessels and the floating cage that causes damage to the flotation chambers affect the buoyancy of the structure with the potential of a total breakdown of the floating cage. Due to more difficult maneuvering conditions, the probability of such hazardous interactions is higher. As seen in Table 4.33, the total RPN is 33% higher for high exposure sites and within the unacceptable area.

System component	Moderate exposure			Old risk			New risk			Change of risk(%)
	Hazard	Hazardous event	Initial consequence	Freq.	Cons.	RPN	Freq.	Cons.	RPN	
Floaters / buoyancy	Heavy equipment	Untreated water entering the system over the floating collar	Lice problem causing severeal treatments	2	3	5	4	3	7	40%
	Well boats and other operating vessels	Collision or powerful impact between vessel and S-CCS.	Severe damage to floaters resulting in loss of buoyancy and total damage of system	1	5	6	3	5	8	33%

Table 4.33: Change analysis for floaters/buoyancy of a rigid system when moving from moderate exposure to higher exposure.

Chapter 5

Results

To investigate the risk of operating different types of S-CCSs in sites with different degrees of exposure, three risk analyses were used. A preliminary hazard analysis was conducted for flexible, semi-rigid, and rigid S-CCSs operating at moderate exposure. The analysis identified hazards and hazardous events threatening the main components of the systems. The hazardous events have several potential outcomes that would affect fish welfare, lice problems, structural damage, escapes of salmon, or the environment. The results from the PHA were compared by conducting a comparative analysis. Further, the results from the PHA were used as a reference risk to investigate how the risk was affected by moving production to less and more exposed sites. The investigation was carried out using a change analysis for all S-CCSs. The results from the risk analysis are presented in the sections below.

A diagram containing the average RPN for the consequence types on the system's main components was made to present the risk picture of farming fish in semi-closed containment systems. There are five sections in the diagram, shown in Figure 5.1, where each section represents the investigated main system components. The main components or systems are water inlet, water outlet, structure/wall, buoyancy/floaters, and dead fish pump. To highlight the varying risk for the different S-CCSs, all S-CCSs are presented in the same diagram. Blue bars represent flexible systems, orange bars represent semi-rigid systems, and grey bars represent rigid systems.

5.1 S-CCSs operating in low exposure

Low-exposure sites offer smaller forces from waves and currents compared to the reference site of moderate exposure. The most considerable risk of producing in flexible structure at low exposure sites is the probability of technical errors or blockage in the water inlet, water outlet, and dead fish pump. These are the three critical components to providing good water quality where fish can live and grow as intended. Also, there are risks of structural damage to the floating collar due to impacts between vessels and the S-CCSs. The risk of impacts causing damage to the floaters is within the ALARP risk area, and risk-reducing measures should be evaluated. Proposed measures are to provide better crew training and improve procedures for vessels entering the production site.

The risk is low and broadly acceptable for both the semi-rigid and rigid structures. The events with the highest risks are mostly concerns of technical failure of the water inlet, water outlet, and dead fish pump that will cause diseases and sub-optimal conditions for the fish. The structures are strongly capable of withstanding the forces from the sea at sites with low exposure. The highest risk of damaging the properties comes from large-power impacts with operating vessels. However, the risks that follow when producing at low-exposure sites are broadly acceptable for all components and categories.

From Figure 5.1, it could be seen that there is a clear tendency of lower risk as the structure gains stiffness. All average risk priority numbers are within the acceptable risk, with no RPN scoring above six. The biggest concern from operating at low exposure is hazardous events causing threats to the water inlet and water outlet. These components are critical for maintaining good fish welfare.

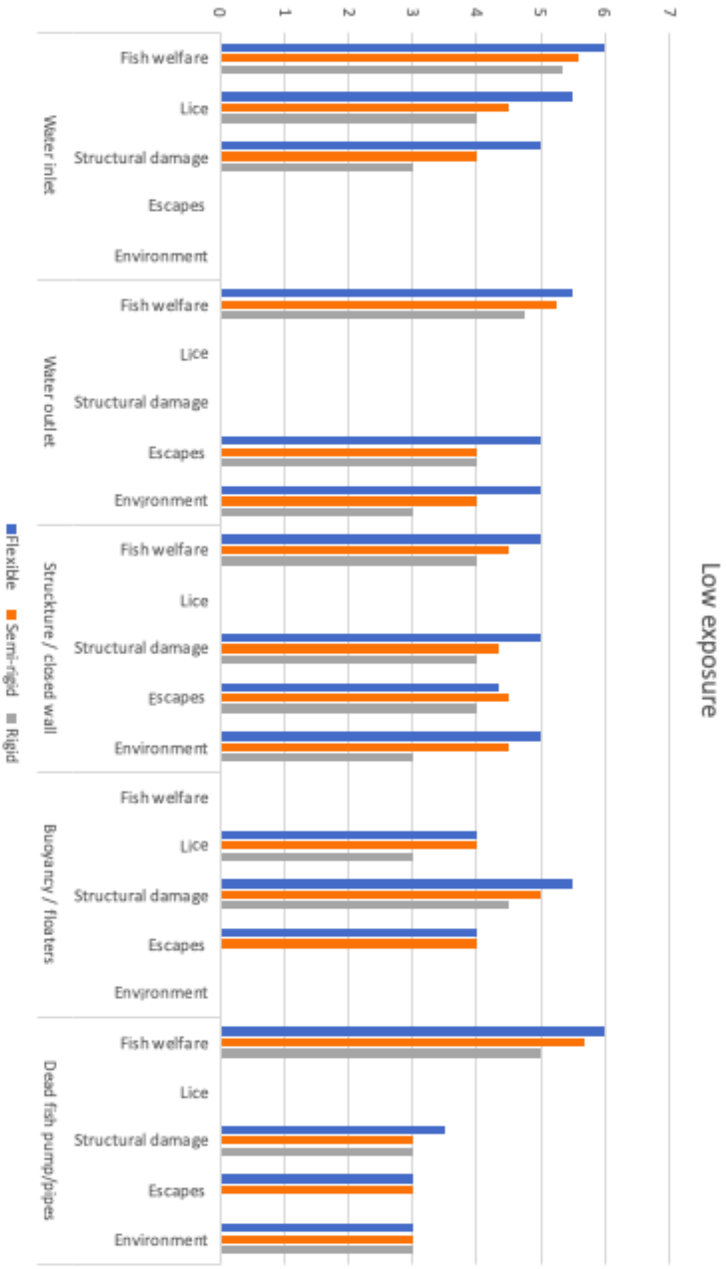


Figure 5.1: Resulting risk comparison for the three types of S-CCSs operating at low exposure.

5.2 S-CCSs operating in moderate exposure

Operating in moderately exposed areas with larger significant wave heights and stronger currents will increase the risk. As seen in Figure 5.2 the risk is, in general, higher for all systems and their components. The consequence type where the risk increases the most is structural damage for all system components. The concern for structural damage is the increased hydrodynamic forces acting on the structures. Especially structural damage to main components for flexible and semi-rigid systems is relevant as their structural designs lack the ability to protect critical equipment and components from large forces from weather and sea. A rigid system is able to provide shelter for the components by using voids designed in the structure.

The main concerns are structural damage and fish welfare for flexible systems, shown as the blue bar in Figure 5.2. These are often strongly connected. Waves and currents are threats to the water inlet pipes, which are given no protection from the structure. Large forces from waves and currents will work on them and cause damage if large enough. For moderate exposure, such forces leading to damage to the pipes are probable, and the risk is within the ALARP area. Cracks on the pipe open the possibility for lice, organisms, and pathogens to enter the production volume and affect the fish's welfare. The risk of such events is acceptable, but risk-reducing measures should be considered. Technical errors are in the water outlet, and dead fish pumps are contributing factors to the relatively high risk of reduced fish welfare. In addition, large forces acting on the components and the bag's motion will affect the components' performance. These systems are crucial to transporting used water, waste solids, and nitrogen out of the production volume. Also, an error or damage to the water outlet will lead to loss of overpressure inside the bag, which will reduce the volume for the fish to live as intended. The RPNs for the flexible cage are below 7 for all components and categories, making it an acceptable risk.

The risk of production in semi-rigid systems at moderate exposure is relatively similar to flexible systems. From the orange bars in Figure 5.2, it could be seen that the primary concern of using semi-rigid systems in moderate exposure is structural damage and reduced fish welfare. The risk of structural damage is mainly due to loads from waves and currents or impacts between operating vessels and the S-CCSs. Structural damage where cracks develop on the water inlet pipe will enable lice to enter the system as the water enter the pipe in the upper layer of the sea. Regarding fish welfare, the major contributors to the risk are technical failures on the water inlet, water outlet, and dead fish system. Also, the effect of sloshing inside the tank has a considerable risk of injuring the fish. The risk of operating a semi-rigid system in moderate exposure is within acceptable areas. However, risk-reducing measures should be evaluated to reduce the risk of damage to the components and reduced fish welfare.

As seen from the grey bar in Figure 5.2, the risks of escapes, lice, and environmental harm are broadly acceptable for rigid structures. The highest risks are hazardous events on the system components that affect fish welfare. Technical errors and fouling on the water inlet systems count for the highest risk, as these will affect the water quality and further the fish's welfare. Also, technical errors in the dead fish pump contain a considerable risk, as the component is meant to transfer waste and dead fish out of the production volume to maintain good water quality. A rigid structure will experience more sloshing inside the cage, potentially harming the fish. At moderate exposure, the risk of severe sloshing is considered acceptable within the ALARP area.

The clear trend that could be seen in Figure 5.2 is that the risk decreases as the stiffness of the structure increases. Protecting critical components for more rigid structures reduces the risk of damage or failures that could lead to severe outcomes.

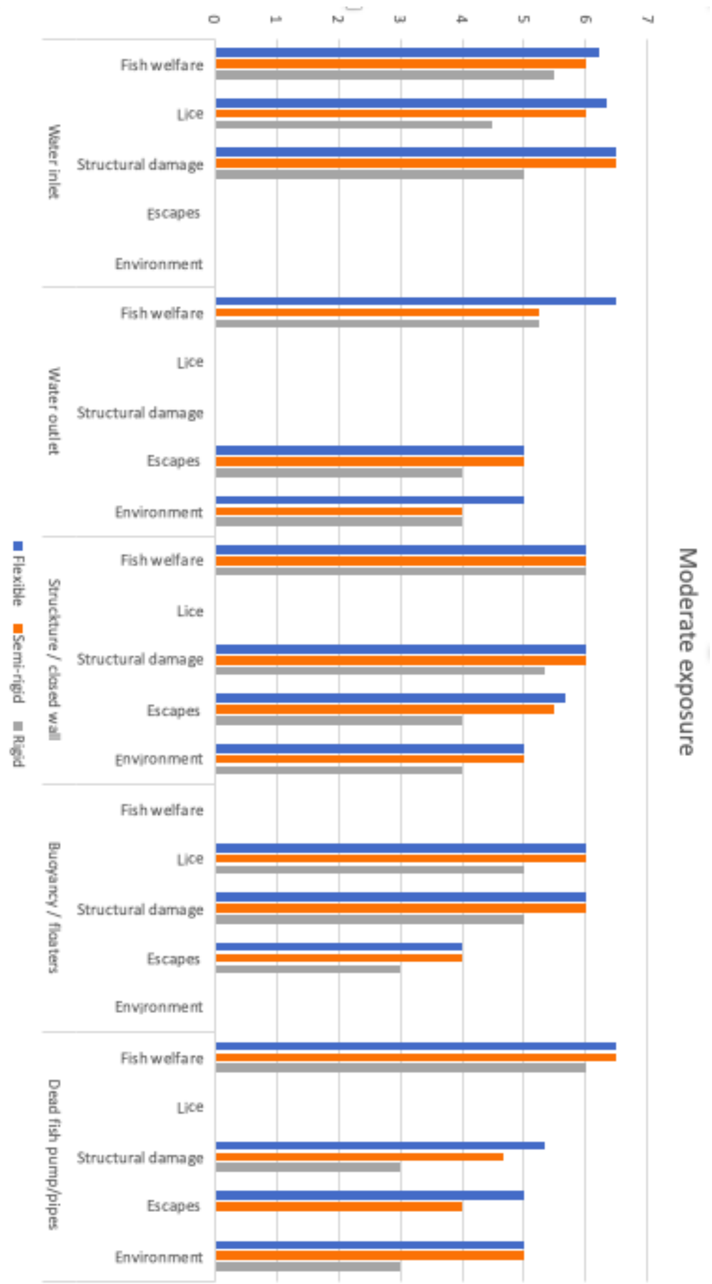


Figure 5.2: Resulting risk comparison for the three types of S-CCSs operating in sites with moderate exposure.

5.3 S-CCSs operating in high exposure

As seen in Figure 5.3, the RPN for the consequence types has increased for all system components. The flexible system, presented as blue bars, have, in general, a higher risk for all system components with one exception. The RPN of severe impacts on fish welfare due to hazardous events for the flexible bag is lower than for semi-rigid and rigid structures. This results from lower sloshing motions within the flexible bag compared to the other systems. The flexible system lacks the ability to protect critical systems, and the water inlet pipe does not have any support from the structure. As a result, the risk of structural damage to the water inlet pipe, and following lice problems due to cracks in the upper part of the inlet pipes, is unacceptable with RPNs over 7. The bag will experience significant motion, from which components mounted on the bag could be damaged. Reduced or increased flow out of the water outlet will, for instance, severely affect fish welfare. The reduced flow will increase the concentration of CO2, TAN, and particles, whereas increased flow will reduce the pressure inside the bag and mitigate the volume for fish to live in.

For the semi-rigid system, represented by the orange bar in Figure 5.3, the system is mostly within an acceptable risk within the ALARP area, where there is a need to consider risk-reducing measures. The system cannot fully protect the water inlet pipes but will support the pipes to reduce the motion. At sites with high exposure, the support does not make up for the enormous forces acting on the component, and the risk of structural damage to the pipes is unacceptable with RPNs above 7. Also, the structure's material will allow for larger sloshing motions compared to the flexible cage. The sloshing motion severely affects the conditions within the production volume, leading to an unacceptable risk concerning fish welfare. The sloshing motion and the external forces from waves and currents also make the risk of structural damage to the enclosed wall unacceptable.

The grey bar in Figure 5.3, representing the rigid system, shows a much lower risk than for flexible and semi-rigid systems. The structure protects critical components in voids within the wall, making the risk of damaging water inlets, water outlets, and dead fish systems low and acceptable. The strength of the material is more capable of withstanding large forces from the sea and potential impacts with operating vessels. However, sloshing motions in a rigid system will be higher and have a severe effect on the fish. Large sloshing motions make the conditions for fish unbearable, with a following high mortality rate, making this the event with the highest risk.

All of the already existing S-CCSs operate in very sheltered areas where they are sheltered from incoming waves with large amplitudes. The floating operating systems are designed for significant wave heights of two meters or below. Operating in larger waves and wave periods closer to the system's natural period is hazardous. In Figure 5.3, it could be seen that the risk increases drastically for all systems compared to the RPNs in lower exposures. Several of the RPNs exceeds the acceptable risk level. The acceptable risk level is an RPN of seven or below. The same tendency of increasing risk for less rigid structures applies to high-exposure sites. However, severe effects on fish welfare due to sloshing inside rigid structures hold the highest risk, just above semi-rigid and flexible structures. This results from more significant sloshing motions developed for more rigid cages, which will injure and kill fish inside. Moreover, the risks of damaging the water inlet pipes and the wall material are unacceptable for flexible and semi-rigid systems.

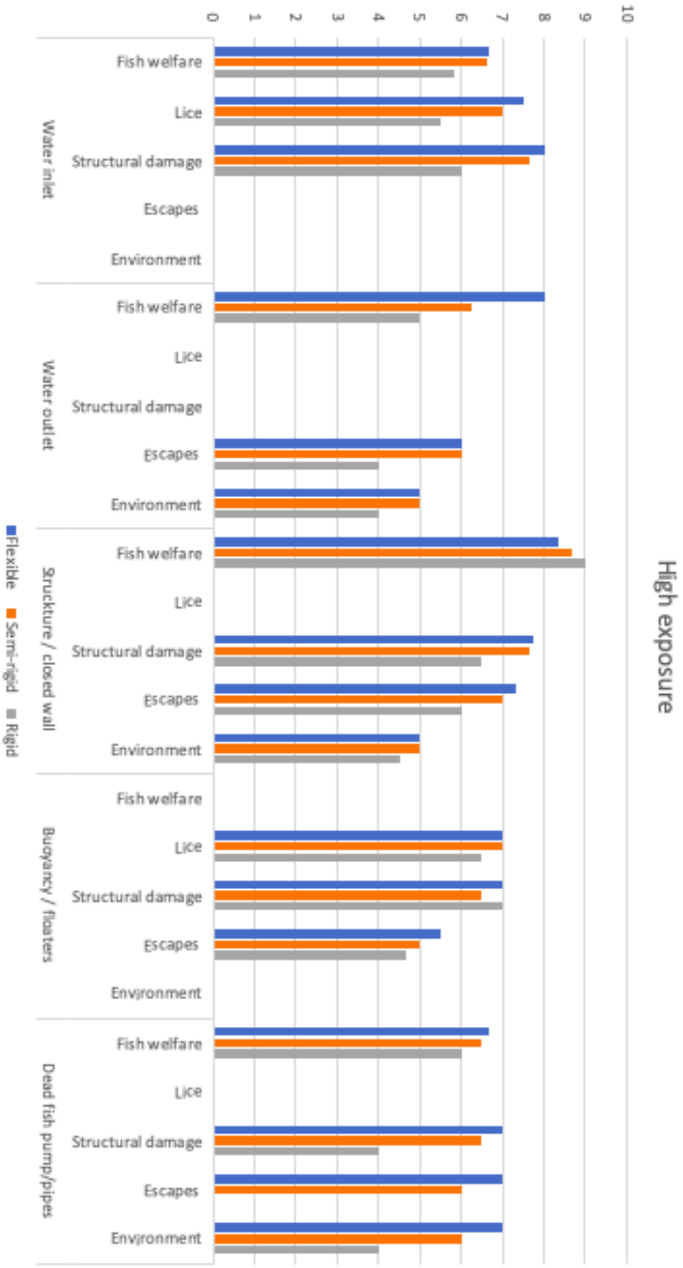


Figure 5.3: Resulting risk comparison for the three types of S-CCSs operating at high exposure sites.

Chapter 6

Discussion

6.1 Results

For all three exposures, production in a rigid structure is deemed the most secure production strategy. The rigid S-CCS have the lowest probability of hazardous events causing severe consequences for all potential outcomes except for reduced fish welfare due to sloshing at high exposure. This is a result of rigid structures developing larger sloshing motions compared to the more flexible alternatives. Further, semi-rigid structures are ranked as the second most secure S-CCS, and flexible structures are considered the least secure S-CCS as the material is more sensitive to large forces, and challenges regarding deformations are unique for these cages. Another influence of the risk has to do with the different structure's ability to protect critical components and equipment. The feasibility of providing shelter for main components in a flexible cage is low without making large modifications to the structure. In comparison, semi-rigid cages do not have the same suitability to provide protection as a rigid structure. However, a semi-rigid structure enables the possibility of mounting support for components exposed to waves and currents. Based on the results of the risk analysis, all three types of S-CCS could operate at low exposure and moderate exposure, but for moderate exposure, risk-reducing measures should be taken. The risk of operating in high exposure is unacceptable for all types, which is reasonable since most of the existing S-CCSs are designed for significant wave heights of 2 meters or less, and none are designed for significant wave heights above 2,5 meters.

The change analysis showed a high risk of moving to more exposed areas. The risks found for the different systems are probably higher than the actual risks of operating them at high-exposure sites. However, the high risks highlight hazardous events that must be dealt with to produce salmon in higher significant wave heights. Also, the high risk indicates that much research must be done, and knowledge must be gained before moving to more exposed sites.

6.2 Risk analysis

In the preliminary hazard analysis, which was the starting point of the risk analysis, a list of hazards and hazardous events was identified for each of the main components of a S-CCS. The list was made based on previous accidents, knowledge gained from the literature review, and a brainstorming process made by the author. The list does not cover all potential hazards that could affect the risk of producing in a S-CCS, and all of the listed hazards might not be of equally high relevance for the total risk picture, but it covers the most important ones. With the aim of comparing the risk for different types of S-CCSs, some of the components in the systems were not covered in the analysis, assuming that the risk will not differ for these components, regardless of a change of exposure or structure. Nevertheless, there will be potential hazards and hazardous events for feeding systems, oxygen supply, and monitoring systems, which should be assessed to get the complete risk picture.

The study objects were delimited to the S-CCSs, the structures, and the main components. In addition to the components mentioned above, mooring systems and mooring lines were left out of the risk analysis to reduce the content of the time-consuming analysis. However, risk assessment of mooring systems is crucial for producing in S-CCS as the mass and forces increase drastically compared to the traditional net pen.

Determining the frequency and consequence of hazardous events was challenging. Few operating S-CCSs that have existed for a short period of time, results in a lack of accident data and design data. Hence, determining the frequency of hazardous events and their following consequence contains many uncertainties. Resulting frequencies and consequences are established from expert judgment based on the author's understanding of the risk with a background in previous accidents and the literature review. As a result, some of the risk priority numbers will not represent the actual risk, but they will highlight potential hazards and hazardous events that must be considered.

6.3 Assumptions and limitations

The risk analyzes were conducted for three types of S-CCSs operating at different degrees of wave exposure. There are many different designs, but the investigations were limited to circular-shaped structures with free surfaces and an open top. Hence, structures like Egget, designed by Hauge Aqua, and FishGLOBE were left out of the analysis. These structures are more spherical-shaped structures with a closed rooftop. These designs mitigate the risk of sloshing due to less free surface area and water line area. It also eliminates the risk of waves entering the system over the top. In addition, designs like the raceway system for Preline are excluded from the analysis. With the heightened interest surrounding semi-closed containment systems, many different designs and concepts will probably arise in the future.

There were several assumptions about the different systems. It was assumed that flexible structures could not protect or provide support system components like water inlets and dead fish pipes. Semi-rigid structures were assumed to have the structural ability to support the water inlet and dead fish pipes. For the rigid system, it was assumed that the rigid structure uses flotation chambers that could provide protection and shelter for the system components. These assumptions are suitable for now, but with the increased focus on S-CCSs, new concepts will be developed with other structural designs.

6.4 Comments of the study

In the risk analysis, it was found that more rigid structures would be beneficial to maintaining the safe production of Atlantic salmon. Many assumptions were made for determining the frequency and consequence of hazardous events. These assumptions might be wrong, leading to resulting risk from the analysis, which does not correspond with the actual risk. On the other hand, the results emphasize relevant hazards that need to be considered when designing a S-CCS. In the future, when more knowledge and available data for producing in S-CCSs, a more exact risk could be calculated. The risk model development gives a great example of how a combination of different risk analysis methods could be used together to identify hazards and hazardous events in an early design phase and examine how the risk is affected by changing the operating environment.

6.5 Further work

In this thesis, many assumptions were made for setting the frequency and consequence due to a lack of data. For further work, collecting more data from existing and new developments will make the frequency and consequence numbering more accurate. In addition, more hazards and hazardous events could be detected, giving a more complete risk for the S-CCSs.

Risk-reducing measures have been proposed for hazards within the ALARP and unacceptable risk levels. Investigating the effect of implementing risk-reducing measures could be carried out and will give an interesting insight into the possibilities of operating S-CCS more exposed. For a more in-depth analysis, a fault tree analysis and event tree analysis could be carried out on the high-risk hazards. The fault tree analysis could detect all causes leading to hazardous events and provide a more accurate estimation of the risk. Further, an event tree analysis could be conducted for the most critical hazards to find many potential outcomes and the probability of each hazard. The fault tree analysis and the event tree analysis will give a better foundation to suggest proactive, to reduce the frequency, and reactive barriers, to prevent or reduce the consequence.

Chapter 7

Conclusion

The Norwegian fish farming industry searches for new production strategies to ensure the growth of the production of Atlantic salmon. Production of post-smolt in flexible, semi-rigid, and rigid S-CCSs arise as a solution, but there are concerns regarding the risk of using such technologies. Three risk analyzes have been carried out to investigate the risk of producing salmon in the different types of S-CCSs with varying degrees of exposure.

The results imply that the risk of producing salmon in S-CCSs at low exposure sites, as the existing systems do today, is an acceptable risk for all systems. Flexible structures experience challenges with deformations, and the lack of protection of main components makes it the S-CCS with the highest risk. The more rigid structures have lower risk as their ability to maintain the shape and protect critical equipment is beneficial from a risk perspective.

Changing the location to areas with moderate exposure have a negative effect on the risk for S-CCSs operating in the sea. Larger forces from waves and currents acting on the structures are a threat to the safety of the system components and the fish within. For all structural alternatives, the risk is found to be acceptable, but risk-reducing measures should be made as they are just within an acceptable level.

Each of the structures is facing severe problems if operating at high-exposure sites. Higher wave amplitudes and periods will cause large sloshing motions within the cages, making it unbearable for fish to live and grow. A more rigid structure will experience more significant sloshing motions, making the risk of increased mortality worse. Also, structural components are threatened by the enlarged hydrodynamic forces. Water inlets and dead fish pumps for flexible and rigid systems are immensely exposed to enormous forces from the sea. The possibility of damage and destruction is too significant for maintaining a safe production. Hence, the risk of producing S-CCSs in high exposure is unacceptable.

Based on the results, it is feasible to produce post-smolt in enclosed fish farms, but there are still many challenges that must be dealt with before using S-CCSs commercially. With today's knowledge and technology, producing Atlantic salmon in closed cages is acceptable up to significant wave heights of 2 m, but risk-reducing measures should be taken. In order to produce in more exposed areas, more knowledge regarding the behavior and response of the cages in the sea is needed. For now, this comes with too high of a risk for the production to be acceptable.

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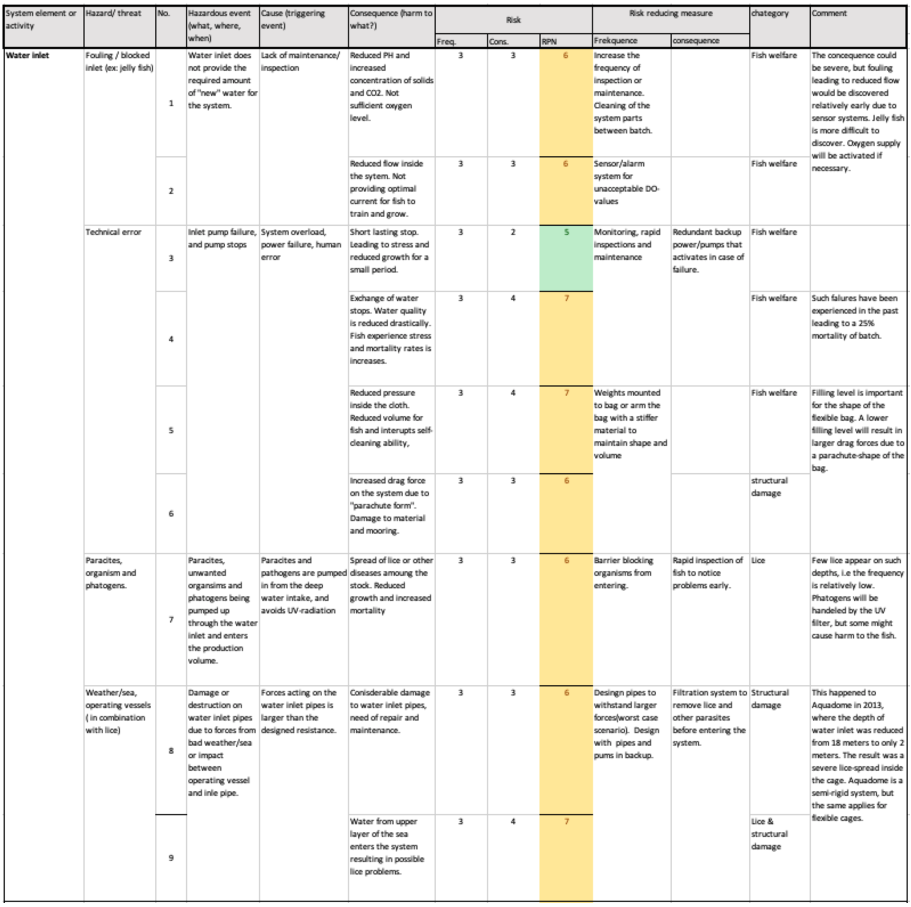
Appendix

A Preliminary hazard analysis of a flexible S-CCS in moderate exposure



System element or activity	Hazard/ threat	No.	Hazardous event (what, where, when)	Cause (triggering event)	Consequence (harm to what?)	Risk			Risk reducing measure		chategory	Comment
						Freq.	Cons.	RPN	Frekquence	consequence		
Water inlet	Fouling / blocked inlet (ex: jelly fish)	1	Water inlet does not provide the required amount of "new" water for the system.	Lack of maintenance/ inspection	Reduced PH and increased concentration of solids and CO2. Not sufficient oxygen level.	3	3	6	Increase the frequency of inspection or maintenance. Cleaning of the system parts between batch.		Fish welfare	The concequence could be severe, but fouling leading to reduced flow would be discovered relatively early due to sensor systems. Jelly fish is more difficult to discover. Oxygen supply will be activated if necessary.
		2			Reduced flow inside the sytem. Not providing optimal current for fish to train and grow.	3	3	6	Sensor/alarm system for unacceptable DO-values		Fish welfare	
	Technical error	3	Inlet pump failure, and pump stops	System overload, power failure, human error	Short lasting stop. Leading to stress and reduced growth for a small period.	3	2	5	Monitoring, rapid inspections and maintenance	Redundant backup power/pumps that activates in case of failure.	Fish welfare	
		4			Exchange of water stops. Water quality is reduced drastically. Fish experience stress and mortality rates is increases.	3	4	7			Fish welfare	Such falures have been experienced in the past leading to a 25% mortality of batch.
		5			Reduced pressure inside the cloth. Reduced volume for fish and interupts self-cleaning ability,	3	4	7	Weights mounted to bag or arm the bag with a stiffer material to maintain shape and volume		Fish welfare	Filling level is important for the shape of the flexible bag. A lower filling level will result in larger drag forces due to a parachute-shape of the bag.
		6			Increased drag force on the system due to "parachute form". Damage to material and mooring.	3	3	6			structural damage	
	Paracites, organism and phatogens.	7	Paracites, unwanted organsims and phatogens being pumped up through the water inlet and enters the production volume.	Paracites and pathogens are pumped in from the deep water intake, and avoids UV-radiation	Spread of lice or other diseases amoung the stock. Reduced growth and increased mortality	3	3	6	Barrier blocking organisms from entering.	Rapid inspection of fish to notice problems early.	Lice	Few lice appear on such depths, i.e the frequency is relatively low. Phatogens will be handeled by the UV filter, but some might cause harm to the fish.
	Weather/sea, operating vessels (in combination with lice)	8	Damage or destruction on water inlet pipes due to forces from bad weather/sea or impact between operating vessel and inle pipe.	Forces acting on the water inlet pipes is larger than the designed resistance.	Conisderable damage to water inlet pipes, need of repair and maintenance.	3	3	6	Desingn pipes to withstand larger forces(worst case scenario). Design with pipes and pums in backup.	Filtration system to remove lice and other parasites before entering the system.	Structural damage	This happened to Aquadome in 2013, where the depth of water inlet was reduced from 18 meters to only 2 meters. The result was a severe lice-spread inside the cage. Aquadome is a semi-rigid system, but the same applies for flexible cages.
		9			Water from upper layer of the sea enters the system resulting in possible lice problems.	3	4	7			Lice & structural damage	

Water outlet	Technical error, human error	1	Loss of overpressure causing reduced change of water through water outlet	-Lack of attention -Lack of training -failure on monitoring/sensor systems	Reduced pressure inside the bag leading to reduced volume, disrupting self-cleaning ability and reducing fish welfare.	3	3	6	Stiffeners mounted in the bag. Redundant water control systems.		Fish welfare	
		2			Reduced pressure leading to increased dragforce and fatigue on mooring system	3	3	6	Mooring designed to endure larger forces.		Structural damage	
	Rough sea	3	Large loads acting on the water outlet system causing filtration failures and damage to the barrier against escapes.	Fatigue on filtration equipment in water outlet. Damage on filtration equipment due to weather/sea in water outlet.	Release of fish feces and feed(sludge) to the local environment.	3	2	5	Increased maintenance		Environment	
		4		Damage to water outlet.	Escapes of fish	2	3	5	Mount a double barrier against escapes. Ex: net on the outside of the bag.		Escapes	In addition to lice, escapes is a large challenge in Norwegian aquaculture. SCCS are ment to eliminate the risk of escapes.
	Blockage on water outlet	5	Reduction of water flow out of the system.	Fouling and sludge blocking the water outlet	Increased consentration of CO2, accumulation of particles and formation of ammonium	3	4	7	Sufficient maintenance and inspection		Fish welfare	Sensor systems will discover early, which result in a low frequency.

Flexible bag	Motion and sharp edges on dead fish pump	1	Damage on material close to the sludge/dead fish pump.	Strong current causing large movement in dead fish pump.	Damage on bag causing a considerable stop in production to repair	3	3	6	Design the connection with no sharp edges. Stronger reinforcement in the eposed area.		Structural damage	
		2			Severe rift in bag, leadin to large amount of escapes(150 000 < X < 500 000)	2	4	6		Double security against escapes(Safety net)	Escapes	RPN for escapes is strict compaared to the other RPN. RPN matrix is taken from NS9415.
	Human error	3	Collecting fish to wellboat using equipment that could damage the material or fish.	-Lack of attention -Lack of training	Escapes of fish	2	3	5	Internal fish collecting systems. Double security from escapes (net).	Double security against escapes(Safety net)	Escapes	Flexible systems lack the structure to implement collecting methods to the system in the same way as for semirigid and rigid structures.
		4			Stress, injuries and mortality among fish	3	3	6	Clear and good procedures.		Fish welfare	
	Snaploads	5	Material damage in the bag enclosure due to snap loads.	Larger waves and periods cuasing snaploads in the flexible clouth. Certain sea states	Wear and tear on material, causing increased maintenance.	4	2	6	Desing for large eigen periods. Sufficient streanght in material. Double net security.		Structural damage	Snapload is a large challenge when designing flexible cages, and is special for flexible cages. It is important to consider the coupling between the internal body of water, the bag and the floater when designing the S-CCS.
		6			Loss of structural integrity of the system. Clotch must be changed	2	4	6			Structural damage	
		7			Large amounts of escapes	2	4	6		Duble security against escapes	escapes	
	Waves	8	Waves with certain periods causing sloshing inside the tank.	Incoming waves with periods close to the liquid sloshing natural period.	Stress and bad environment for fish to live in.	3	3	6	Desing for large eigen periods. Sufficient strenght in material. Double net security.	Modify the current inducers to reduce development of internal waves.	Fish welfare	Because of the flexible bag, there will be more damping in a flexible system sloshing will not occure as much compared to semi-rigid and rigid structures.
		9			Damage and fatigue on the flexible fabric/structure.	3	3	6			Structural damage	

Bouyancy/floaters	Heavy equipment, fouling and Waves	1	Untreated water entering the system over the floating collar due to waves and to low freeboard.	Low freeboard due to large weights of equipment and structure. Little/no reserve bouyancy from the flexible bag.	Lice entering the system. Short lasting lice infections.	4	2	6	-Avoid floating collar with small cross-section radius. -Enclose the top of the S-CCS with a roof. -Safety wall around the floaters(ex: plexiglass)	Inspection of fish to discover infections early.	Lice	Some closed containment systems is closed at the top to avoid over splashing of waves. The threat of water splasing over increases for larger sea.
		2			Lice and phatogens problem causing severeal treatments and diseases among the stock	3	3	6			Lice	
		3			Fish escapes	2	2	4		Monting a wall around the floaters (ex: plexiglass), will prevent crew falling in to the sea as well.	Escapes	
	Well boats or other operating vessels	4	Collision or powerfull interaction with vessel and S-CCS.	Lack of training, Difficult weather and sea.	Minor damage on floaters	4	2	6	-Better procedures. -Mount impact dampers on the floaters.		Structural damage	Because a flexible S-CCS system does not have reserve bouyancy a damage to floaters will be critical.
		5			Severe damage to floaters resulting in loss of boyancy and destruction of main parts of the system	2	4	6			Structural damage	

Dead fish pump/pipe	Current & waves or vessels	1	*Loads from waves and current acting on the dead fish pump and pipe. *Vessels operating near the dead fish pipe makes contact with the pipe.	*Pipe is mounted on the outside of the bag where it is exposed to loads from currents and waves. *Wellboat or other vessels operating with low awareness.	Minor damage on pipes.	4	1	5	Implementing a dead fish pump/pipe system that is more protected from the sea i.e provide shelter in the design phase. Could be on the inside of the bag.		Structural damage	For flexible cages dead fish pipes are mostly mounted outside of the bag. This could cause motion on the pipes when being exposed to forces from the sea.
		2			Clogged pipes due to larger deformations on pipe. Accumulation of sludge in the system.	3	3	6		Implement a possibility of increasing suction power.	Structural damage	
		3			Torn off dead fish pipe, releasing sludge to the local environment	2	3	5			Environment	
		4			Torn off dead fish pipe, causing escapes and release of sludge	2	3	5		Safety net as double barrier against escapes	Escapes	
	Technical error	5	Deadfish pump stopping - dead fish, fish feed feces are not leaving the production volume.	*Too small pumpe/pipe cross section. *Fouling *system overload	Accumulation of sludge in the system for a short period reducing the water quality.	4	2	6	*Sensor systems *Redundant power systems. *Increased maintenance.		Fish welfare	If sludge accumulates in the system, toxic gasses (H2S) will develop inside the production volume.
		6			Pumps stop working for a long time, and toxic gasses evolves and spread in the production water. Mass mortality.	2	5	7			Fish welfare	

B Preliminary hazard analysis of a semi-rigid S-CCS in moderate exposure

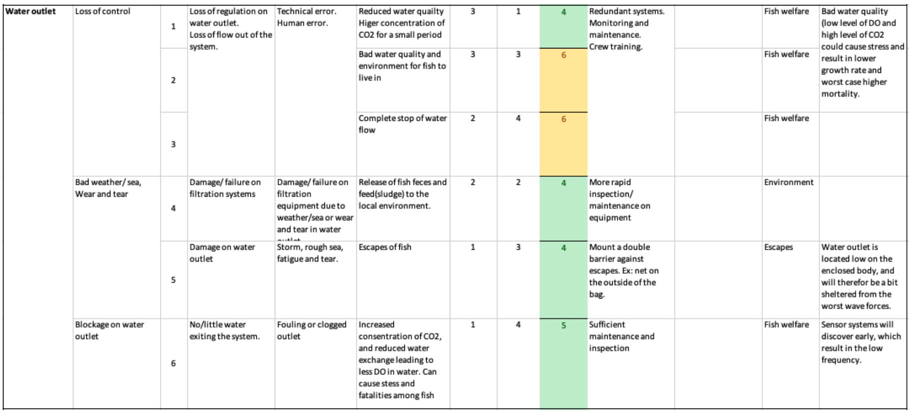
System element or activity	Hazard/ threat	No.	Hazardous event (what, where, when)	Cause (triggering event)	Consequence (harm to what?)	Risk			Risk reducing measure		Chategory	Comment
						Freq.	Cons.	RPN	frequency	Concequnce		
Water inlet	Fouling / blockage (ex: jellyfish)	1	Water inlet does not provide the required amount of "new" water for the system.	Lack of maintenance/ inspection	Reduced flow inside the sytem causing reduced training, apetite and environment for the fish.	3	3	6	Increase the frequency of inspection or maintenance. Alarm systems and sensors at the water inlet and water quality several locations inside the system.	Backup systems in case blockage or failure.	Fish welfare	The concequence could be severe, but fouling leading to reduced flow would be discovered relatively early due to sensor systems. Blockage is more difficult to avoid. Oxygen supply will be activated if necessary, but water quality will still be inadequate.
		2			Drastic change in water quality. Increased consentration of CO2, ammonia, dissolved solids. High mortality rate.	2	4	6			fish welfare	
	Technical error	3	Pumps stops providing new water to the system.	System overload, power failure, human error	Short lasting stop leading to stress and reduced growth for a small period.	3	2	5	Optimize maintenance and inspection of equipment. Monitoring of the critical parts	Redundant backup power system that activates in case of failure.	fish welfare	Such falures have been experienced in the past leading to a 25% mortality of a batch and decrease in growth rate during the whole life cycle.
		4			Exchange of water stops for a longer period. Water quality is reduced drastically. Lots of stress for fish and possibly severe mortality rate.	3	4	7			Fish welfare	
	Paracites, organisms and phatogens	5	Paracites. organisms and pathogens entering the system.	Paracites and bacteria pumped in from the deep water intake, and avoids filtration and UV-radiation.	Lice infections and diseases spread among the batch.	3	2	5	Ensure adequate filtration for inlet water.	Intensify lice inspection intervall.	Lice	By using UV-radiation and deep water intake the risk is relatively low. But experiences with jellyfish have caused increased mortality.
	Weather, rough sea and vessels. In addition, lice	6	Weather and sea causing large loads on water inlet pipe and difficult manouvering conditions for vessels.	Forces acting on the water inlet pipes is larger than the designed load resistance.	Considerable damage to water inlet pipe causing need for repair and maintenance	3	3	6	A design that protects the pipes or pipes to withstand larger forces. Design with more pipes and pums in backup.		Structural damage	This happened to Aquadome during a storm in 2013, where the depth of water inlet was reduced from 18 meters to only 2 meters. The result was a severe lice-infection inside the cage.
		7			Water from upper layer of the sea enters the system resulting in lice entering the system due to damage on pipe.	3	4	7		Increased filtration of water before entering the current indusers.	Structural damage & Lice	
Water outlet	Techical error	1	Reduced/loss of water exchange due to water not exiting the system as rapidly as intended.	Error with sensors, automation or pump control	Short lasting error leading to some increased consentration of particles and CO2	2	2	4	Monitoring and inspection	Redundant backup systems	fish welfare	Bad water quality (low level of DO and high level of CO2 could cause stress and result in lower growth rate and worst case higher mortality.
		2			Long lasting error leading to bad water quality, where mortalities occur.	2	4	6			fish welfare	
	Bad weather/ rough sea. Fatigue	3	Wear and tear or damage on filtration systems at the water outlet.	Damage/ failure on filtration equipment due to weather/sea or wear and tear in water outlet.	Release of fish feces and feed(sludge) to the local environment.	2	2	4	More rapid inspection/ maintenance on equipment		Environment	More rapid inspection and maintenance will reduce the risk of the scenarion happening, but it is difficult to proviide a concequence reducing measure.
		4		Storm, rough sea, fatigue and tear.	Escapes of fish	2	3	5	Design with protection for water outlet.	Mount a double security agains escapes. Ex: a grid over the outlet.	Escapes	Water outlet is located low on the enclosed body, and will therefor be a somewhat sheltered from the worst wave forces. Therefor the low frequency.
	Blockage on water outlet	5	No/little water exiting the system as a result of clougged outlet	Fouling, waste from feed, feces or dead fish	Increased consentration of CO2, and reduced water exchange leading to bad environment for the fish. Can cause stess and mortality among fish	3	2	5	Sufficient maintenance and inspection. Sensor systems. Cleanign of the system and the system parts between batches.	Redundant systems. PH control.	fish welfare	Sensor systems will discover early, but it could take time to fix the clogged outlets resulting in detoriated water quality. Formation of hydrogen sulfide is a new challenge that producers was not aware about(CtrlAQUA - Åsa Maria Espmark)
		6			Same as above, but in addition development of toxic gasses(H2S) and NH4+ and NH3.	2	4	6			Fish welfare	

Structure/wall	Well boats and operating vessels	1	Powerful impact between wellboat and S-CCS.	-difficult sea -Lack of attention -Lack of competence	Minor damage to wall	4	2	6	Install a barrier between the floater and well boat, ex: impact damper on the ouside of the floatin collor to take the hit. Better training for crew and improved	Rapid inspection of the system to disover damage.	Structural damage	Small marks on the structure will occur occationally, but will not always lead to damage. Larger damages to material is more rarely. Fish escpaes follows the RPN matrix proposed by NS 9415 and is therefore unacceptable for lower RPN-values.
		2			Hole/crack in material Lice entering the system	3	3	6				
		3			Structure damage leading to large amount of escapes.	2	3	5		Double barrier against escpaes.	Escapes	
		4			Destruction of system. System can no longer be used.	1	5	6			Structural damage	
	Bad weather and rough sea	5	Loss of structural integrity of the S-CCS due to damage caused by wind and waves.	Large loads from storm, bad weather and sea.	Structural collapse	2	5	7	Desing for more extreme weather, currents and large waves		Structural damage	Happened to AquaDome during a technical test. Material failed to withstand forces, and the structure collapsed.
		6			Structural damage leading to escapes of fish	2	4	6		Safety net as a double barrier against escapes	Escapes	
		7			System parts, sludge and dead fish released to the environment	2	3	5			Environment	
	Waves and wave periods	8	Waves with certain periods causing sloshing inside the tank.	Structure endures wave periods close to its eigen period.	Stress and bad environment for fish to live in.	3	3	6	Design for large eigen periods. Possible to use current inducers to affect the development of internal waves	Modify the current inducers to reduce development of internal waves.	Fish welfare	Sloshing is one of the main challenges for exposed locations when enclosing the system. Semi-rigid and rigid structures will experience more sloshing compared to flexible structures.
		9			Considirable damage on structure	3	3	6			Structural damage	

Bouyancy/ floaters	Heavy equipment/ weather/ fouling	1	Untreated water entering the system over the floating collar	Low freeboard due to large weights of equipment and structure. More reserve bouynacy that for flexible cages.	Lice entering the system. Short lasting lice infections.	4	2	6	-Avoid floating collar with small cross-section radius. -Enclose the top of the S-CCS with a roof or provide a barrier around the floater(wall/plexiglass).	Inspection of fish to discover infections early.	Lice	Adjusting the draught and freebord for a flexible cage is difficult without reducing the filling level and causing deformations. The threat of water splasing over increases for larger sea.
		2			Lice problem causing severeal treatments	3	3	6			Lice	
		3			Small amount of fish escapes	2	2	4			Escapes	
	Well boats or other vessels	4	Collision or powerfull interaction with vessel and S-CCS.	Lack of training, Difficult weather and sea.	Minor damage on system	3	2	5	Better training for crew and well made procedures when operating close to or on the system.	Impact dampers around the cage.	Structural damage	Because a flexible S-CCS system does not have reserve bouyancy a damage to floaters will be critical.
		5			Severe damage to floaters resulting in loss of boyancy and total damage of system	2	5	7			Structural damage	
Dead fish pump/pipe	Current & waves or vessels	1	Damage on the pipes when: *Loads from waves and current acting on the dead fish pump and pipe. *Vessels operating near the dead fish pipe makes contact with it.	*Pipe is mounted on the outside of the bag where it is exposed to loads from currents and waves. *Wellboat or other vessels operating with low awareness.	Minor damage on pipes.	3	1	4	Implementing a dead fish pump/pipe system that is more protected from the sea. Design to withstand larger forces. Improved procedures for crew on vessels when working close to the cage.		Structural da	For flexible cages and most semi-rigid dead fish pipes are mostly mounted outside of the bag. This could cause motion on the pipes when being exposed to forces from the sea. Spill of sludge could cause over fertilzed seabed in the local area.
		2			Clogged pipes due to larger deformations on pipe	2	3	5		Increase suction power of the pumps.	Structural da	
		3			Torn off dead fish pipe, releasing sludge to the local environment	2	3	5			Environment & Structural damage	
		4			Torn off dead fish pipe component in the bottom of the structure, causing escapes	2	2	4		Safety net as a double barrier against escapes	escapes	
	Technical error	5	Deadfish pump stopping - dead fish, fish feed feces are not leaving the production volume.	*Too small pumpe/pipe cross section. *Fouling *system overload	Accumulation of sludge in the system for a short period reducing the water quality.	4	2	6	*Sensors and monitoring *maintenance *Redundant power systems.	Improved technology and equipment to ensure sufficient selfcleaning abilit.	Fish welfare	If sludge accumulates in the system concentration of particles and nitogen will increase. Toxic gasses (H2S) could develop inside the production volume as well.
		6			Pumps stop working for a long time, and toxic gasses evolves and spread in the production water. Not livable contidions for the fish.	2	5	7			Fish welfare	

C Preliminary hazard analysis of a rigid S-CCS in moderate exposure.

System element or activity	Hazard/ threat	No.	Hazardous event (what, where, when)	Cause (triggering event)	Consequence (harm to what?)	Risk			Risk reducing measure		Risk category	Comment
						Freq.	Cons.	RPN	Frequency	Consequence		
Water inlet	Fouling/ blockage	1	Water inlet does not provide the required amount of "new" water for the system.	Bio-fouling or high density of jelly fish on the water inlet.	Reduced flow inside the sytem. Mitigating self-cleaning ability of system. Less current for fish to "train". Reduced water quality and fish welfare.	2	3	5	Increase the frequency of inspection or maintenance.	Possibility to increase water flow of pipes that aren't blocked	Fish welfare	The concequence could be severe, but fouling leading to reduced flow would be discovered relatively early due to sensor systems. Oxygen supply will be activated if necessary.
		2			Reduced dissoved oxygen inside the tank. Fish experience stress.	2	4	6	Sensor/alarm system for unacceptable DO-, PH, TAN, and CO2 values		Fish welfare	
	Technical error	3	Inlet pump failure.	System overload, power failure, human error	Short lasting stop of water pumps.	3	2	5	Increased maintenance and inspection of the critcal system parts.	Redundant backup power/pumps that activates in case of failure.	Fish welfare	Such falures have been experienced in the past leading to a 25% mortality of a batch and decrease in growth rate during the whole life cycle. A rigid system will have a better possibility to be equipped with backup systems.
		4			Exchange of water stops for a longer period. Water quality is reduced drastically. Lots of stress for fish and possibly severe mortality rate.	2	4	6			Fish welfare	
		5			Mass mortality	2	5	7			Fish welfare	
	Lice/ paracites, organisms(ex: jelly fish) and phatogens	6	Paracites, organisms and bacterias entering the system.	Paracites and bacteria pumped in from the deep water intake, and avoids UV-radiation and filtration.	Lice or diseases spread, reducing healt for fish.	3	2	5	Adjustable water inlet depth. Suficient filtration systems.	Monitoring and inspection to treat for infections early.	Lice	By using UV-radiation and deep water intake the risk is relatively low
	Strong weather and rough sea	7	Storm, bad weather, large waves, strong current acting on the inlet pipes and cause damage to pipe(s).	Forces acting on the water inlet pipes is larger than the designed resistance.	considerable damage on water inlet pipe. Need for repair and maintenance	2	3	5	Desingn that protects the pipes or pipes to withstand larger forces where the pipes are not protected(below the structure).	Redundant backup pumps/pipes.	Lice	The rigid structure is more rubust, and could protect the water inlet pipes increasingly.
		8			Water from upper layer of the sea enters the system due to water inlet damage resulting in lice problems.	1	3	4			Structural damage	Water inlet is mostly sheltered in the upper layers of the sea.



Water outlet	Loss of control	1	Loss of regulation on water outlet. Loss of flow out of the system.	Technical error. Human error.	Reduced water quailty Higer concentration of CO2 for a small period	3	1	4	Redundant systems. Monitoring and maintenance. Crew training.		Fish welfare	Bad water quality (low level of DO and high level of CO2 could cause stress and result in lower growth rate and worst case higher mortality.
		2			Bad water quality and environment for fish to live in	3	3	6			Fish welfare	
		3			Complete stop of water flow	2	4	6			Fish welfare	
	Bad weather/ sea, Wear and tear	4	Damage/ failure on filtration systems	Damage/ failure on filtration equipment due to weather/sea or wear and tear in water	Release of fish feces and feed(sludge) to the local environment.	2	2	4	More rapid inspection/ maintenance on equipment		Environment	
		5	Damage on water outlet	Storm, rough sea, fatigue and tear.	Escapes of fish	1	3	4	Mount a double barrier against escapes. Ex: net on the outside of the bag.		Escapes	Water outlet is located low on the enclosed body, and will therefor be a bit sheltered from the worst wave forces.
	Blockage on water outlet	6	No/little water exiting the system.	Fouling or clogged outlet	Increased consentration of CO2, and reduced water exchange leading to less DO in water. Can cause stess and fatalities among fish	1	4	5	Sufficient maintenance and inspection		Fish welfare	Sensor systems will discover early, which result in the low frequency.

Structure/wall	Well boats and operationg vessels	1	Powerful impact between wellboat and S-CCS.	-difficult sea -Lack of attention -Lack of competence	minor damage to wall/floater	3	2	5	Install a barrier between the floater and well boat. Material on the ouside of the floatin collor to take the hit.		structural damage	Small marks on the structure will occur occationally, but will not always lead to damage. Larger damages to material is more rare. Fish escpaes follows the RPN matrix proposed by NS 9415 and is therefore unacceptable for lower RPN-values.
		2			Hole/crack in structure - lice entering	2	2	4			structural damage	
		3			Loss of structural integrity leading to large amount of escapes.	1	3	4	Better training for crew.		Escapes	
		4			Destruction of the structure. System breakdown.	1	5	6			Structural damage	
		5			Release of fish feces and feed(sludge) to the local environment.	2	2	4			Environment	
	Weather and rough sea	6	Large loads from large waves and strong wind acting on the rigid cage causing fatigue and stress.	Actual loads exceeds the designed.	Wear and tear on mooring lines	3	2	5	Desing for extreme weather, currents and large waves		Structural damage	A structural damage of Tank 1 from AgriMarine happened during a storm in 2011. A large crack in the structure cased escapes and emergency harvest.
		7			Mooring line snaps due to large forces	2	4	6			Structural damage	
		8			Fatigue over time cauasin destruction on main structure of the S-CCS.	2	4	6	Desing for extreme weather, currents and large waves		structural damage	
	Certain wave periods	9	Waves with certain periods close to the sloshing natural perood causing sloshing inside the tank.	Structure endures wave periods close to the natural sloshing period.	Stress and bad environment for fish to live in. Could cause injuries and possibly mortality.	3	3	6	Design for large eigen periods. Possible to use current inducers to affect the development of internal waves	Modify the current inducers to reduce development of internal waves.	Fish welfare	Rigid structrues has little damping of internal waves and is therefore more vulnerable for sloshing. However the structure is more robust and can withstand larger forces.
		10			considerably damage on structure and escapes	3	2	5			Structural damage and escapes	

Bouyancy/ floaters	Heavy equipment/ weather	1	Untreated water entering the system over the floating collar	Water reaching over freeboard due to large weights of equipment and structure.	Lice entering the system. Short lasting lice infections.	3	2	5	-Design with sufficient freeboard. 'Semi-rigid III'! -Enclose the top of the S-CCS with a roof.		Lice	Rigid structrues obtains more reserve bouyancy compared to both semi-rigid and flexible cages.
		2			Lice problem causing severeal treatments	2	3	5			Lice	
		3			Small amount of fish escapes	1	2	3			Escapes	
	Well boats or other vessels	4	Collision or powerfull interaction with vessel and S-CCS.	Lack of training, Difficult weather and sea.	Minor damage on system	2	2	4			Structural damage	Floaters are mostly divided into sections, resulting in the structure maintaining boyancy if damage occurs. Aslo a rigid structure contains relatively large reserve boyancy from the structure.
		5			Severe damage to floaters resulting in loss of boyancy and total damage of system	1	5	6			Structural damage	
Dead fish pump/pipe	Current & waves or vessels	1	*Loads from waves and current acting on the dead fish pump and pipe. *Vessels operating near the dead fish pipe.	*Pipe is mounted on the outside of the bag where it is exposed to loads from currents and waves. *Wellboat or other vessels operating with low awareness.	small deformations on pipes.	1	1	2	Implementing a dead fish pump/pipe system that is more protected from the sea. Design to withstand larger forces.		Structural damage	For a rigid structure dead fish pumps and pipes will be protected within the structure. This reduces the frequency of damaging the pipes from vessels or weather a lot.
		2			Clogged pipes due to larger deformations on pipe	1	3	4		Increase suction power of the pumps.	Structural damage	
		3			Torn off dead fish pipe, releasing sludge to the local environment	1	2	3			Environment	
	Technical error	4	Deadfish pump stopping - dead fish, fish feed feces are not leaving the production volume.	*Too small pumpe/pipe cross section. *Fouling *system overload	Accumulation of sludge in the system for a short period reducing the water quality.	3	2	5	*Sensor systems *Redundant power systems. *Improved technology and equipment to ensure sufficient selfcleaning abilit	Improved technology and equipment to ensure sufficient selfcleaning abilit.	Fish welfare	
		5			Pumps stop working for a long time, and toxic gasses evolves and spread in the production water. Not livable contidions for the fish.	2	5	7			Fish welfare	

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