Master's thesis

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

Jørgen Nesje

Change in risk picture by going from a conventional sea cage to a submersible cage concept in Norwegian fish farming

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
Co-supervisor: Stein Haugen
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MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2022

For stud.techn. Jørgen Nesje

"Change in risk picture by going from a conventional sea cage to a submersible cage concept in Norwegian fish farming."

Background

Globally, Norway is the leading producer and exporter of Atlantic salmon. However, national production growth has stagnated over the last decade, and the industry is currently facing sustainability and production challenges related to sea lice and area utilization. In this regard, ScaleAQ has designed a submersible sea cage concept (Midgard Subsea system) that intends to decrease sea lice infestation and allow for production in more exposed areas along the coast. The design is more or less a revision of a conventional sea cage, where the primary change is a submerged net bag. The system composes several other modifications, many as a result of submergence, which altogether has altered the technical and operational aspects of convectional fish farming. Consequently, the risk picture also changes, which is the main motivation of this master thesis.

Objective

The overall aim of the master thesis is to determine how the differences between the Midgard subsea system and a conventional sea cage will influence the risk picture. First, by comparing the two sea cage systems, the thesis aims to identify technical and operational differences. A well-established system description of a conventional sea cage shall provide the basis for comparison. Assessment and evaluation of risk shall address the identified differences and find out if the differences change the risk positively, negatively, or both. The main objective of the thesis is to determine how each of the identified differences will impact the risk of a set of well-known hazardous events in Norwegian fish farming.

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

a. A brief introduction to Norwegian aquaculture
b. A literature study to gain insight and knowledge on risk issues in the industry.
c. Document relevant theory and methodology for addressing and solving the problem,
d. Detailed system descriptions of both the conventional sea cage and Midgard subsea system.
e. Perform a Change Analysis to reach the thesis objectives.
f. Present and evaluate the changed risk picture, and potentially propose risk-reducing measures.
g. Discuss strengths and improvement potential in one's approach and work.
h. Suggestions for further work.

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

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

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

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

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

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

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett, NTNU.

Co-supervisor: Stein Haugen, Safetec Nordic.

Company contact: Morten Holthe, morten.holthe@scaleaq.com.

Deadline: 11.06.2022

Preface

This thesis is written to fulfil the requirements for the Master of Science degree in Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis counts as 30 credits and symbolizes the end of two educational years at NTNU. My background and interest in marine industries, particularly Norwegian fish farming, have been an important motivation in the master thesis and for building on my bachelor's degree in Product and System Design. The thesis is written during the spring semester of 2022. It investigates how the risk associated with traditional fish farming alerts by substituting a conventional sea cage with a submersible concept developed by ScaleAQ. The work builds on insight gained during my specialization project, carried out in the preceding semester (Nesje, 2021).

The Norwegian fish farming industry is currently facing an exciting industrial shift, and I would first like to thank ScaleAQ for giving me the opportunity to work with their innovative sea cage concept. Studying the risk issues in the industry and gaining insight into new farming technologies has been a true learning experience and has increased my interest in the field. Secondary, I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett, for advice and feedback throughout the semester. I also want to give a special thanks to my co-supervisor in Safetec Nordic, Stein Haugen, who, although external, has been available during the whole thesis period and provided me with guidance and insightful discussions, especially related to the methodology. Lastly, I would like to express my gratitude towards the following persons, who have all provided me with valuable information. Their help is acknowledged and appreciated.

Ingunn Marie Holmen - PhD candidate and researcher in SINTEF - Input on risk in conventional fish farming.

Ole Folkedal - Researcher at the Institute of Marine Research (IMR) - Input on fish welfare and growth.

Otto Igland - Area manager in MOWI - Input on technical and operational aspects of conventional fish farming,

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Trondheim, 10th June 2022

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Summary

The Norwegian fish farming industry is currently facing sustainability and production challenges related to sea lice and area utilization. In this regard, ScaleAQ has re-designed a conventional sea cage to submerge the net bag (the design is conceptual). The objective of this thesis has been to identify technical and operational differences between the submersible concept and a conventional sea cage and, most importantly, determine how these identified differences will impact the risk to a set of well-known hazardous events in Norwegian fish farming. The thesis has aimed to assess both the positive and negative effects of the identified differences.

NS 5814 is the governing standard for risk assessment in the industry, and the work of the thesis is carried out according to the guiding principles of the standard. The core elements of the Change Analysis described by Rausand and Haugen (2020) have been applied to address the thesis's objectives. The latter method uses the terms *basic* system and *new* for indicating which system that are known (basic) and which is modified (new). The conventional sea cage corresponds to the basic system.

Four risk dimensions, or values, were found to be relevant for the thesis. The following eleven hazardous events were selected, where $\mathrm{RPN}_{i,B}$ indicates the current risk level for the basic system. As mentioned, the thesis has aimed to understand how each identified difference impacts the risk of these events.

Value	(i)	Hazardous event	$\mathrm{RPN}_{i,B}$	Result: Change in risk	Result: Uncertainty
Personnel	1	Occupational accidents	7	Positive	Low
	2	Man overboard	6	No change	Low
Environment	3	Fish escape	6	Positive	Medium
	4	Littering to sea	7	Positive	Low
	5	Sea lice and disease spread - wild stock	9	Positive	Low
Material	6	Structural damage	6	Positive	Medium
	7	Breakdown of sea cage	6	Negative	Low
Fish welfare	8	Compromised welfare	8	Negative	Low
	9	Fish death/increased mortality	7	Negative	Low
	10	Sea lice and disease spread	8	Positive	Low
	11	Loss of growth	5	Negative	Low

The result was 40 identified differences between the submersible concept and the conventional sea cage, of which 30 had a positive and/or negative effect on the selected events. These 30 were assigned as *key differences*. To determine the risk impact of each key difference has been the main objective, and the reader is advised to see Section 6.4 for the result.

Considering all the positive and negative risk impacts in a holistic perspective, the risk to personnel and environment are the values that, with a fairly low degree of uncertainty, showed a reduced risk with the submersible concept. Important key differences in this regard were less activity and equipment on the sea cage. Environmental risk to wild stock had, as expected, reduced risk in terms of lice and disease spread. However, the risk of fish escape did not show the same potential. Certainly, there were many positive effects related to fish escape, however, the system also introduced three uniquely new escape events that must gain utmost attention to secure an overall positive change in risk. A total of 18 effects on fish escape risk were registered (both positive and negative).

Risk to material assets was positively influenced by in-depth sheltering of auxiliary equipment, but the risk of structural breakdown increased due to a more remote site location. Regarding risk to fish welfare, apart from lice spread, the change in the risk picture was found to be negative. Considering all four hazardous events, the differences contributed to 25 negative effects, where sub-optimal environmental conditions and significantly reduced monitoring capabilities of welfare and feeding were central causes for increased risk to fish welfare. Lastly, the thesis also includes 21 suggested risk reduction measures, which were assigned to key differences that had a risk impact with an ALARP risk level or higher.

Sammendrag

Norsk oppdrettsnæring står i dag overfor bærekrafts- og produksjonsutfordringer knyttet til lakselus og arealutnyttelse. I denne forbindelse har ScaleAQ redesignet ei konvensjonell oppdrettsmerd til å kunne senke not posen (design er konseptuelt). Fokuset til denne masteroppgaven har vært å identifisere tekniske og operasjonelle forskjeller mellom det nedsenkbare konseptet og en konvensjonell merd, hvor hovedmålet har vært å finne ut hvordan disse identifiserte forskjellene vil påvirke risikoen for et utvalgte uønska hendelser i norsk lakseoppdrett. Oppgaven har hatt som mål å vurdere både positive og negative effekter av de identifiserte forskjellene.

NS 5814 er den gjeldende standarden for risikovurdering i bransjen, og arbeidet i avhandlingen er utført etter standardens førende prinsipper for risikovurdering. Hovedelementene i Endringsanalysen beskrevet av Rausand and Haugen (2020) er brukt for å adressere oppgavens mål. Sistnevnte bruker begrepene *basic* system og *new* system for å indikere hvilket system som er kjent (basic) og hvilket som er modifisert (new). Den konvensjonelle merden tilsvarer *basic*.

Fire risikodimensjoner, eller verdier, var relevante for oppgavens formål. De følgende elleve uønska hendelsene ble valgt, hvor RPN$_{i,B}$ indikerer dagens risikonivå for ei konvensjonell merd. Som nevnt har oppgaven som mål å forstå hvordan hver identifisert forskjell påvirker risikoen for disse hendelsene.

Verdi	(i)	Uønsket hendelse.	RPN$_{i,B}$	Resultat: Endring i risiko	Resultat: Usikkerhet
Personale	1	Arbeidsulykke	7	Positiv	Lav
	2	Mann overbord	6	Ingen endring	Lav
Miljø	3	Rømning av fisk	6	Positiv	Medium
	4	Forsøpling til havet	7	Positiv	Lav
	5	Lakselus og sykdomsspredning - villaks	9	Positiv	Lav
Materiale	6	Strukturelle skade	6	Positiv	Medium
	7	Sammenbrudd av merd	6	Negativ	Lav
Fiskevelferd	8	Redusert velferd	8	Negativ	Lav
	9	Fiskedød/økt dødelighet	7	Negativ	Lav
	10	Lakselus og sykdomsspredning	8	Positiv	Lav
	11	Vekst-tap	5	Negativ	Lav

Resultatet var 40 identifiserte forskjeller mellom det nedsenkbare konseptet og den konvensjonelle merden, hvorav 30 hadde en positiv og/eller negativ effekt på de utvalgte hendelsene. Disse 30 ble tilordnet som *nøkkelforskjeller*. Hovedmålet har vært å fastslå risiko påvirkningen av hver nøkkelforskjell, og leseren anbefales å gå til kapittel 6.4 for å se resultatet.

Dersom man tar i betraktning alle positive og negative risiko påvirkninger i et helhetlig perspektiv, er risiko for personale og miljø de verdiene som med en ganske liten usikkerhet har redusert risiko med det nedsenkbare konseptet. Viktige nøkkelforskjeller i denne forbindelse var mindre aktivitet og utstyr på flytekragen. Risiko for villaks hadde som forventet redusert risiko i form av lus og sykdomsspredning, men risikoen for rømming viste imidlertid ikke det samme potensialet. Riktignok var det mange positive effekter knyttet til rømming av fisk, men systemet introduserte også tre unike rømningshendelser. Disse nye hendelsene må få høy prioritering for å sikre en samlet positiv endring i risikobilde for rømning. Totalt ble det registrert 18 effekter for rømmingsrisiko (både positive og negative).

Risikoen for materielle verdier ble positivt påvirket ved å skjerme ekstra-utstyr i det nedsenka miljøet, men samtidig økte risikoen for strukturelt sammenbrudd på grunn av en mer avsidesliggende plassering. Når det gjelder risiko for fiskevelferden, sett vekk fra spredning av lus, er endringen i risikobilde funnet til å være negativ. Dersom man tar alle de fire uønska hendelsene i betraktning, ble det registrert 25 negative effekter, der ugunstige miljøforhold og betydelig redusert overvåkingsevne av velferd og fôring var sentrale årsaker til økt risiko for fiskevelferd. Til slutt skal det nevnes at oppgaven også inkluderer 21 foreslåtte risikoreduserende tiltak. Disse ble tildelt nøkkelforskjeller som hadde en risikopåvirkning med et ALARP-risikonivå eller høyere.

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1 Introduction

1.1 Background and motivation

According to the most recent projections by United Nations (2021), the world population is expected to reach 9.7 billion in 2050. Currently, the earth houses almost 7.9 billion people; of these, more than 800 million are affected by hunger (WFP, 2022). In 2019, 135 million suffered from acute hunger, which to a large degree is caused by downturns in the economy, climate change, and man-made conflicts (United Nations, 2022a). The recent global issue of COVID-19 drastically made the situation worse, and after two years of pandemic, the number of people suffering acute hunger increased to 276 million people according to USGLC (2022). The latter states that the doubling in seriously food-insecure people is a result of decreased incomes and disrupted food chains, where the poorest countries still are experiencing severe effects of the COVID-19 pandemic.

Recent years with destructive development in terms of hunger are now aggravated by the ongoing war in Ukraine. The man-made conflict forces Ukrainians out of their homes and deprives their income. Further, the two countries are large suppliers of wheat, as well as the Russian invasion creates adverse ripple effects by increasing the prices of sunflower, maize, and oil (WFP, 2022). By the end of 2022, the World Food Programme (2022) has estimated that an additional 47 million will suffer acute hunger, increasing the total to 323 million from the pre-war baseline of 276 million. Overall, the world is currently facing destructive hunger patterns, and United Nations (2022a) emphasizes the need for profound changes in the food production system in order to sustainably nourish the current hungry people, as well as an additional 2 billion in the years to come.

The Norwegian aquaculture industry has a high ambition of providing the global market with sustainable food in the future, and has previously announced a goal of fivefold increased production by 2050 (Norwegian Industries, 2017). Norway is the leading exporter and producer of Atlantic salmon worldwide, but the production has stagnated over the last decade due to several sustainability challenges (Ministry of Trade and Fisheries, 2021). Conventional farming is experiencing several issues related to safeguarding personnel, fish, and the surrounding environment. However, the primary environmental challenges in Norwegian fish farming are the adverse effects on the wild stock due to escaped fish and sea lice (IMR, 2021c). The production is currently regulated on the basis of lice numbers, that is, the "traffic light system" (Directorate of Fisheries, 2021c). The lice are considered the main bottleneck for further expansion of the industry (The Federation of Norwegian Industries, 2017). The coastal challenge related to sea lice, in addition to other conflicting interests with local communities, tourists, and fisheries, has resulted in stricter management in terms of allowing the establishment of new sites and/or granting of more production license (I. M. Holmen, 2022). Utilizing areas in more exposed coastal areas or even further offshore can increase site availability. However, the conventional technology is not designed to withstand the environmental loads present in these remote locations.

In 2015, the government created a temporary arrangement to help the industry solve the challenges related to environmental protection and area utilization (Directorate of Fisheries, 2022b). The so-called "development licences" involved financial support and were awarded to companies that introduced considerable innovative technology to the industry. Knowledge sharing was an essential part of the strategy, and it was a good opportunity for Norwegian aquaculture to expand and develop into a more sustainable food industry.

In 2016, ScaleAQ applied for a development license with their Midgard Subsea system, then called Aqualine Subsea system. The system addresses the abovementioned challenges by submerging the net bag, which consequently can reduce sea lice pressure and enable production in more exposed coastal areas. Lice infestation rates will most likely decrease because sea lice are said to be present in the upper water layers (Guragain et al., 2021). Production in more exposed areas will be possible as fish and critical equipment are sheltered from harmful surface events. The Midgard subsea system is more or less a revision of a conventional sea cage, with the primary change of submerging the net bag. However, there are consequential changes due to the submergence, and several elements have changed compared to a conventional sea cage, both technically and operationally. Challenges to feeding, monitoring, and air availability arise as a result of submergence, and many parts of the system are still at conceptual design levels. Overall, the concept has alerted the technical and operational aspects of conventional fish farming. Consequently, the risk picture also changes, which is the main motivation of the master thesis.

The risk picture in conventional farming is associated with several risk dimensions: Risk to personnel, fish welfare, environment, material, and food safety. Further, there are several hazardous events related to the different risk dimensions, such as occupational accidents, fish escape, fish death, etc. And since the Midgard subsea system is a reworked version of a conventional sea cage, it is of high interest and importance to understand how the planned modifications will, both positively and negatively, impact the risk of well-known hazardous events in fish farming.

1.2 Research objectives

The objective of the master thesis is to determine how the differences between the Midgard subsea system and a conventional sea cage will influence the risk picture. First, by comparing the two sea cage systems, the thesis aims to identify both technical and operational differences. A well-established system description of a conventional sea cage shall provide the basis for comparison. Assessment and evaluation of risk shall address the identified differences and find out if the differences change the risk positively, negatively, or both. A set of well-known hazardous events in fish farming is to be established, and the main objective is to determine how each of the identified differences will impact the risk of the selected events.

1.3 Scope and limitations

The Change Analysis described by Rausand and Haugen (2020) is to be applied for the purpose of the thesis. The work of the thesis should be executed based on the core elements and principles described by the latter. However, as the method description is somewhat limited, a part of the work will be to adapt the method for the thesis objectives and create customized worksheets/templates. This decision was made together with one of the book's authors, Stein Haugen.

Moreover, the thesis will exclusively focus on the grow-out phase of the salmon production cycle, excluding land facilities related to smolt production and slaughtering. Further, the system boundary is to be established around the sea cage. Other technical and operational aspects related to the fish farm site are only to be considered if the element crosses the system boundary or is essential to the system's integrity and function.

The level of detail regarding system description is settled to component-level. More specifically, this is to the level of auxiliary equipment according to NS 9415 and the components that constitute the particular auxiliary equipment. How the components are assembled is not applicable, e.g., what sub-components that compose a feed spreader. Fastening or interfaces between components shall be considered.

In terms of risk assessment, the thesis is limited to the technical and operational perspectives of fish farming. Financial risk related to the new system is outside the scope of the thesis. Further, the organizational perspective and potential reorganization or other changes related to management, business policies, and regimes shall not be considered. Lastly, change in structural risk due to new environmental loads in a more exposed location is to be handled in structural analysis/detailed engineering and without the scope of this risk analysis.

1.4 Structure of the report

The paper starts with a literature review (Section 2), presenting background material related to Norwegian aquaculture and what defines risk in the industry, as well as relevant risk assessment theory. Section 3 describes the Change Analysis according to Rausand and Haugen (2020) before presenting how the method is applied for the purpose of the thesis. Section 4 and Section 5 covers the two system descriptions and the identified differences. Section 6 presents the result of the change analysis. The section creates a risk assessment framework before determining the risk impact of each difference. At the end of the result section, the result is discussed with respect to each hazardous event (Section 6.5). The last part of the thesis discusses the overall result and work of the thesis and provides recommendations for further work.

2 Literature review

This section present relevant literature and background material for the purpose of this thesis. It is mainly related to Norwegian aquaculture and what defines risk in the industry, as well as theory related to the discipline of performing risk assessments. The written material is, to a large extent, sourced from the project thesis written by the author during the preceding fall semester (Nesje, 2021).

2.1 Norwegian Aquaculture

Norwegian Aquaculture is the second-largest export industry in the country and plays an important role in the global seafood market (Ministry of Trade and Fisheries, 2021). In terms of biomass, China is the major fish farmer, accounting for almost 60% of the aquaculture production in 2018 (FAO, 2020). Norway's share was only 1.65%. However, the Atlantic salmon production in Norway is important for driving technological innovation in the global industry. This section will further discuss Norway's role in a global perspective, before presenting the national perspective and discussing what challenges the industry is currently facing. Lastly, it briefly presents the life cycle of a farmed salmon.

2.1.1 Global perspective

The global aquaculture production has increased by 527% in the period 1990-2018, and it is expected to grow (FAO, n.d.[b]). In terms of marine aquaculture, excluding seaweed, it's expected that aquaculture production will approach the same level as capture fish by mid-century (DNV, 2021). Fisheries have been relatively stable since 1990, and without optimizing the fishery techniques and increasing the utility rate, growth in captured fisheries production would not be sustainable. Thus, increased aquaculture production is set to play a critical role in securing supplies of food for a global population that is projected to reach 9.7 billion by 2050. This would undoubtedly contribute to the Sustainable Development Goal (SDG) no.2 - *End hunger, achieve food security and improved nutrition and promote sustainable agriculture* The aquaculture sector encompasses many opportunities for enabling sustainable development, especially in the achievement of SDG 14 - *Conserve and sustainably use the oceans, seas and marine resources for sustainable development.* The reference to the SDGs: (United Nations, 2022b). There are strong linkages between the SDGs, and since SDG 14 has direct implications for aquaculture, good progress towards the ten sub-targets of SDG 14 will result in positive effects to closely related SDGs, such as SDG 2, 8, 9, 11, and 13. According to Singh et al. (2018), SDG 14 is related to all other SDGs and that 38% of SDGs are dependent on the achievement of SDG 14 in order to succeed. This proves the importance of future development in the aquaculture industry. Norway's position and challenges in this industrial development are reflected in the next paragraph.

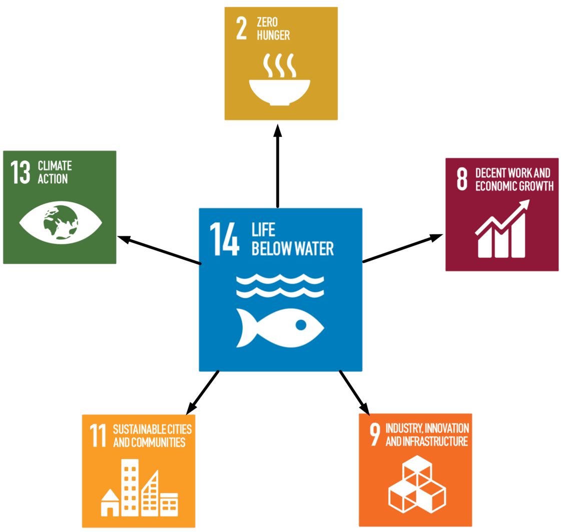

Figure 1: Progress of SDG 14 and spin-off effects

According to FAO (2020), Norway's marine Atlantic salmon aquaculture is one of the most technologically advanced and profitable fish production in the world. The global forecast report by DNV (2021) states that marine aquaculture will more than double by 2050, rising from 30 million tons per year to 74 $\frac{Mt}{yr}$ (excluding seaweed). The forecast implies that these future production levels can only be met sustainably by heavyset development and technology innovation. In this regard, Norway's intensive aquaculture industry is at the forefront and is currently showing a rapid pace of product innovation (FAO, 2020). Currently, technological innovation in the Norwegian aquaculture industry is driven by the environmental challenges related to salmon lice, fish escapes, and area utilization (The Federation of Norwegian Industries, 2017). This is further discussed in Section 2.1.2

2.1.2 National perspective

The Norwegian aquaculture industry has experienced exceptional growth since the start in the 1970s and is today one of the most important export industries in the country (The Federation of Norwegian Industries, 2017). In 2020, the total biomass production of Atlantic salmon in Norway reached approximately 1,3 million tons, corresponding to an export value of approximately 70 billion NOK (Directorate of Fisheries, 2020). In addition to creating values in the national economy, the industry provides jobs and positive spin-off effects that are of high value to local societies. According to the Directorate of Fisheries, approximately 9000 were employed in the production of salmonids (salmon, trout, and rainbow trout) in 2020, which indicates an 80% increment over the preceding decade (Directorate of Fisheries, 2020). This supports the fact of a fast-growing industry.

However, the growth in production has stagnated over the last few years (I. M. Holmen et al., 2021), and further expansion is not likely until the sustainability challenges related to production are mitigated (The Federation of Norwegian Industries, 2017). The production takes place in sheltered coastal areas, and with increased production comes negative ecological consequences. More precisely, these are environmental sustainability issues such as sea lice, fish escape, and waste left on the seabed. Additionally, there are issues related to fish welfare, as well as social sustainability challenges related to human injuries and fatalities. Nevertheless, the sea lice are as previously mentioned the main bottleneck for increasing the production in the industry.

The salmon lice is an ectoparasite, creating skin lesions and open wounds, and consequently creating bad fish welfare for both the migrating wild salmon and farmed ones. Moreover, the lice are said to be residing in the upper water layers (Guragain et al., 2021). The salmon is usually present in the same area due to water quality, feeding, and swimming bladder adjustment (Stien et al., 2021). And in traditional sea cages, this consequently brings high infestation risk. The hypothesized term "lice-belt" is frequently used and typically refers to the zone ranging from the sea surface to 10 meters below it, however, there is no exact definition. Furthermore, the on-demand delousing processes bring significant operational costs for the fish farmers, as well as the operation may impact fish welfare. Overall, the increased sea lice level is identified as the greatest environmental challenge in Norwegian aquaculture Utne et al., 2017.

Another environmental challenge that is given a lot of focus, is escaped salmon. Farmed salmon that escape interacts with the wild population and create negative biological effects in terms of genetic interaction and spreading of disease and parasites. According to I. M. Holmen et al., 2021, a total of 1,770,00 farmed salmon escaped in the period 2010-2016, and since the technology and operations are much the same nowadays, this is still a great risk and threat to the environment.

2.1.3 Production cycle of Atlantic salmon

The production cycle of Atlantic salmon in Norway is approximately three years. The process is initiated in a controlled freshwater environment, where eggs are fertilized and the fish grow into approximately 100 grams. The freshwater phase varies from 12-16 months. Subsequently, the salmon, now called *smolt*, is transferred to seawater cages where it starts its grow-out phase. The fish grows into weights at approximately 4-5 kg over a period of 14-24 months. The time differs mainly due to the variation in seawater temperature throughout seasons and across regions. Fish growth is heavily dependent on temperature, but factors such as feed control, stress, disease, and individual strength/genetics also impact the growth rate. When the salmon has reached harvestable weight, it is transferred to primary processing plants. At this stage, the fish are slaughtered, gutted and processed, before getting distributed to the market. The process is illustrated in Figure 2. This paragraph is based on descriptions by MOWI (2015).

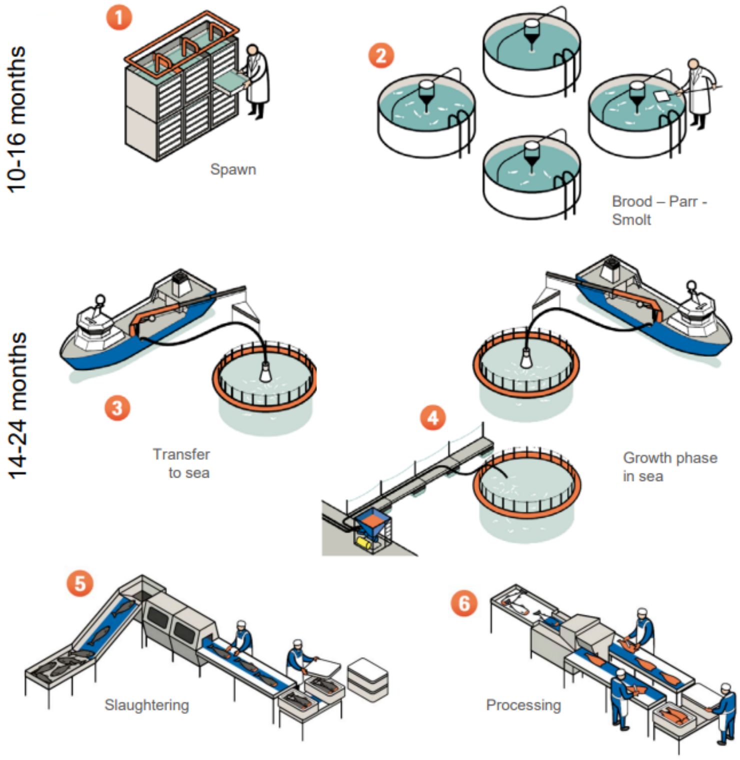

Figure 2: The Atlantic salmon production cycle (MOWI, 2015)

2.2 Safety and risk in Norwegian Aquaculture

2.2.1 Current status

The grow-out phase in Norwegian fish farming is associated with work and operations in harsh environment. Safety for personnel, fish welfare, and integrity of the fish farm are vulnerable and largely affected by changes in wind, waves, and current. In terms of occupational accident rates, the operators in Norwegian fish farming have the second most dangerous profession in the country (I. Holmen et al., 2017). In the period 1982-2015, there were a total of 35 fatalities in Norwegian aquaculture, where many of them are related to operations at the fish farm (S. M. Holen et al., 2018b).

Safety can be defined as the absence of accidents, where an accident is an event involving an unplanned and unacceptable loss (Leveson, 2011). In Norwegian fish farming, the focus on occupational safety has enhanced since the early 1970s, and safety gained increased focus and became a topic of research in the mid-2000s (S. M. Holen, 2019). Work related to the use of vessels and operations involving cranes has been a central focus during engineering risk analysis and technology development. Further, the industry has seen a structural shift into larger companies, which has contributed to implementing safety management through internal control and systematic approaches (S. M. Holen, 2019). Health, Safety, and Environment (HSE) - tools and processes have been increasingly applied in relation to daily operations, courses, meetings, and procedures. Risk assessment and safe planning of operations are used more than before, for instance in terms of SJA (Safe job analysis). However, a study describing the current status of risk assessment in the industry (I. M. Holmen et al., 2018), found several deviations when comparing towards the recommended standard for risk assessment (NS 5814), and that it was variation in quality and to which extent different companies applied and implemented risk assessments.

In other words, despite the fact of positive development in terms of risk and safety management, the industry has room for improvement. Compared to other industries such as the offshore oil and gas industry, fewer resources are allocated for safety work and there is less motivation for performing risk assessments (S. M. Holen, 2019). Risk management and safety will probably not be less important in the coming years, as Norwegian fish farming may become the country's leading ocean industry in the future (I. M. Holmen et al., 2018). Additionally, as discussed in Section 2.1.2, the industry challenges have become a driving force for technological innovation and development, which also bring great opportunities for developing risk management in the industry. But, at the same time, the technology also introduce new hazards and risk elements.

2.2.2 Governing regulations and standards

Norwegian aquaculture is a multidisciplinary industry that affects the surrounding society and environment. Coastal area management, allocation of fish farm licenses, planning and establishment of sites, inspection of fish welfare and health, food production and environmental protection are aspects that need control and supervision (I. M. Holmen et al., 2018). These aspects are allocated to six different regulatory authorities, making the regulatory structure fragmented and complex, and which are experienced as problematic for the industry (Robertsen et al., 2016). The regulation and requirements for safety and risk assessment is also fragmented, and comprise the five following regulatory authorities: The Directorate of Fisheries, Food Safety Authority, Norwegian Maritime Authority, Norwegian Labour Inspection Agency, and the County Administration (S. M. Holen, 2019). They are responsible for the regulations concerning fish welfare, food safety, fish farm technical standard, vessel design and equipment, health, work environment and safety, and the environment (I. M. Holmen et al., 2018).

Regarding standards, the Norwegian standard NS 9415: *Floating aquaculture farms - Site survey, design, execution and use*, is the governing standard for technical conditions and requirements for Norwegian fish farms. However, the standard is not regulatory for the aquaculture industry. Thus, Norwegian Ministry of Trade, Industry and Fisheries developed the NYTEK Regulation: *Regulation on technical requirements for floating aquaculture plants*, which has an overall aim to prevent fish escape by ensuring adequate technical condition of the farms (Ministry of Trade and Fisheries, 2011). The NYTEK regulation ensures compliance with requirements for site investigation, aquaculture facilities, main components, and accessories by referring to NS 9415. Both the regulation and the standard have recently been revised (NYTEK22(Not published) and NS 9415:2021), where the main motivation and need for revisions has been the industrial shift and rapid technology growth which the industry is currently facing (Directorate of Fisheries, 2021b).

While NYTEK is the governing regulation in terms of technical requirements, the operational requirements are governed by: *Regulation on the Operation of Aquaculture Production Sites* (Ministry of Trade, Industry and Fisheries, 2021). Another relevant regulation is the *Regulations on the Control of Salmon Lice in Aquaculture Plants* (Ministry of Trade, Industry and Fisheries, 2016a).

In terms of risk and safety, NS 9415 refers to the Norwegian Standard NS 5814: *Requirements for risk assessment*. The standard is also revised in 2021, and functions as a framework for those performing risk assessments. The standard and process of risk assessment are studied in more detail in Section 2.5. Furthermore, as previously mentioned, the regulation of risk assessment is fragmented and involves five different authorities. Consequently, the risk management is handled by several parts of company management systems (I. M. Holmen et al., 2018). Yang et al. (2020) propose five different risk dimensions that could be used in a single management system, resulting in a more holistic and unified risk evaluation for the fish farms. The five risk dimensions are presented in Section 2.4.

2.3 A traditional fish farm

This section present an overview of a traditional Norwegian fish farm and its mooring. The sea cage is the object of the thesis and is to be described in detail later in the analysis. Thus, this section intends to give a simple introduction of the fish farm as a whole.

A typical Norwegian fish farm facility is illustrated in Figure 3. The farm normally consists of six to 12 plastic collar sea cages, where the number of cages is set according to the site and production license (I. M. Holmen et al., 2018). The salmon is fed with pellets that are transported from the feeding barge through plastic pipes. The feeding control is usually managed from the feeding barge by a fish farmer. However, some companies perform multiple site feeding from remote operation centers, located onshore. Furthermore, the feeding barge consists of silos for feed storage, a feeding system, as well as rooms, workshops offices, and accommodation for the staff. There are typical 2-3 working vessels at the site, available for transportation, daily routines, and crane operations. The fish farmers are responsible for feeding, daily inspections and maintenance of the site, whereas the farm manager is responsible for personnel safety and production management.

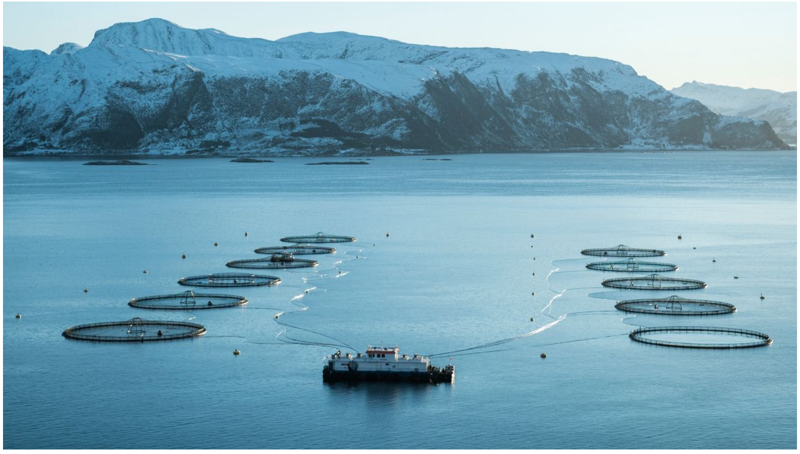

Figure 3: A conventional fish farm (TU, 2021)

The cage is typically moored as shown in Figure 4. The moorings system comprises a submerged framework that enables several cages to be moored in series by the means of bridles and couplings plates. The framework is furthermore anchored to the sea bottom through mooring lines and anchors, or bolts if rock surfaces. The mooring system is usually pre-stressed, as pre-stressed systems are suitable for flexible structures, and enable an even force distribution over the entire farm (Lekang, 2020). An important functionality of the mooring system is to avoid transfer of high vertical forces to the cages, as the floating collar needs to counteract such forces by increased buoyancy capacity. The frame usually consists of heavy-duty ropes and is lowered to 5-8m to avoid conflicts with vessels operating close to the cages. The barge is moored independently of the sea cages.

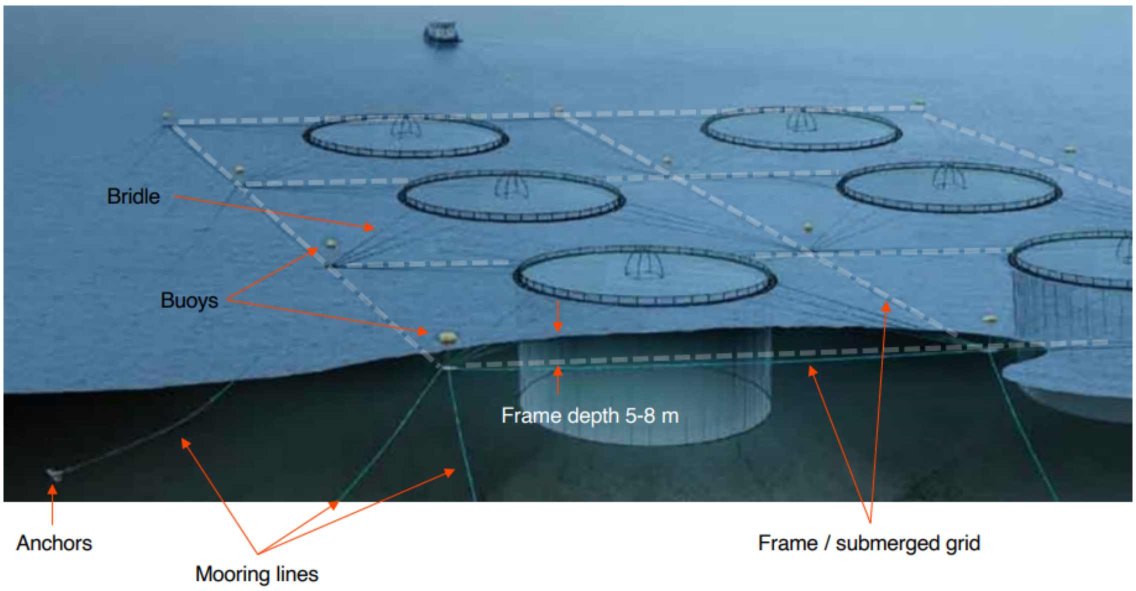

Figure 4: Mooring system (Lader, 2020)

2.4 The five dimensions of risk

The five dimensions of risk that Yang et al. (2020) suggested are: risk to material assets, to personnel, to fish welfare, to the environment, and to food safety - Figure 5. These are values influenced by the fish farming industry and which should be protected - values both *inside* the system boundaries of the farm (personnel, fish, and material assets) and values *outside* (environment and food safety). These five dimensions need to be considered in a holistic perspective when assessing risk in fish farming (Yang et al., 2020).

Figure 5: The five dimensions of risk in fish farming

2.4.1 Risk to personnel

This risk dimension concern risk to people at the farm, which can be both internal and external personnel. As discussed in Section 2.2.1, Norwegian sea-based aquaculture is the second most dangerous profession in Norway. Regarding injuries, fish farmers are among the most exposed, based on accident statistics (S. M. Holen et al., 2018a).

S. M. Holen et al. (2018a) investigated injuries in Norwegian aquaculture during the period 2001-2014, and the three main injury modes were *fall*, *blow from an object*, and *entanglement or crush*. Injuries documented within these three modes have very often occurred during work on vessels. Falls are prone to happen when working on wet/icy deck surfaces and movement between vessel and quay/cage. The vessels are equipped with cranes and capstans, which have contributed to many injuries in the categories *blow from an object* and *entanglement or crush*. The use of crane and falling objects from the crane contributed to almost one-third of the injuries related to object blows in 2010-2014, whereas entanglement and crush were often a result of crushing between ropes and capstans, or otherwise getting caught in chains/ropes during crane operations.

2.4.2 Risk to fish welfare

In terms of assessing risk related to new designs in aquaculture, it's important to consider fish welfare. The design phase should be guided by biological premises, as not accounting for the salmon's needs will bring economical risk and raise ethical questions to the production.

Animal welfare could be defined as: *the quality of life as perceived by the animal itself* (Noble et al., 2018). The welfare needs of salmon can broadly be divided into four different categories; The availability of resources, water environment, health, and behavioral freedom. Figure 6 shows main welfare concerns linked to each category. A fulfilling of these needs will affect positively the salmon's mental health and thereby bring a good welfare status of the fish (Noble et al., 2018).

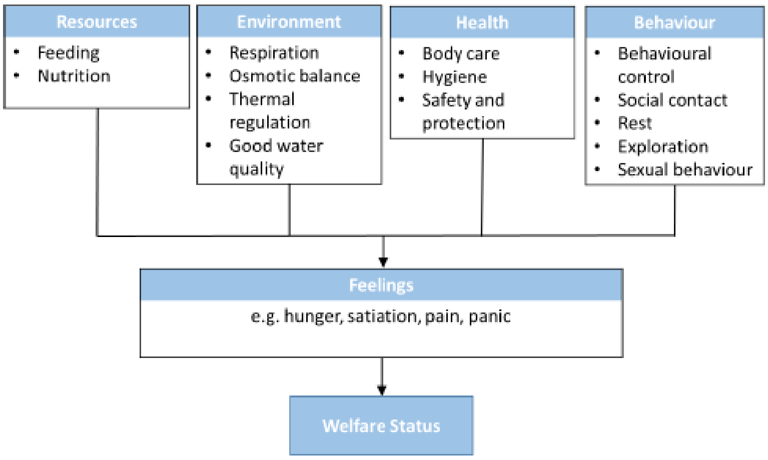

Figure 6: Welfare needs of salmon (Noble et al., 2018)

Norwegian aquaculture industry facing challenges related to fish welfare and high mortality rates. A report from 2019 states mortality of approximately 16% in the Norwegian fish farming industry (NVI, 2019). The reason for insufficient welfare and high mortality comprise a lot of factors and vary from different locations. However, central concerns are diseases, parasites, predators, stress, environmental conditions, nutrition, and individual strength and genetics. The ectoparasite of salmon lice is as mentioned previously one of the main challenges, leading to bad welfare, increased handling (delousing), increased operational expenses, and affecting the wild population. Mortality is often a result of a combination of these welfare concerns, as illustrated in Figure 7 .

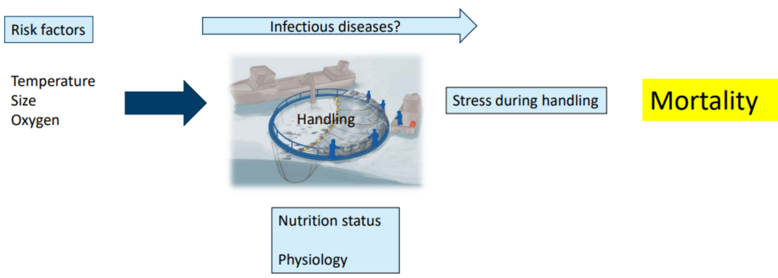

Figure 7: Mortality of salmon as a result of several factors (SINTEF, 2021)

2.4.3 Risk to environment

The sea cages are open structures, with the net bag as the only barrier towards the surrounding environment. This brings several aspects to the risk dimension, which are presented underneath Figure 8.

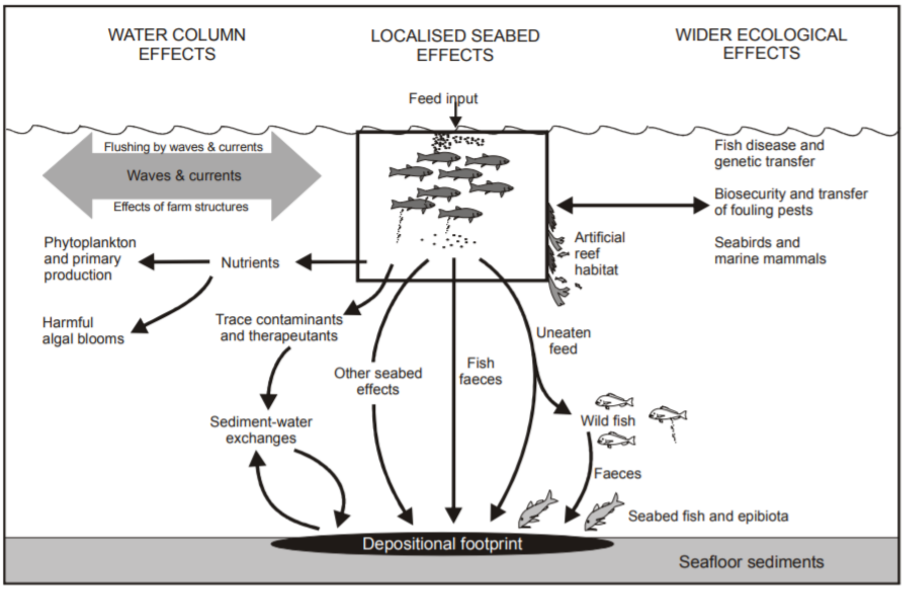

Figure 8: Ecological effects of finfish aquaculture (Forrest et al., 2007)

Waste and pollution:

The high concentration of salmons in the limited area of the sea cage may result in notipceable amounts of solid and dissolved nutrients released to the surrounding aquatic environment.Inorganic nitrogen, phosphorus, and carbon (CO_2) are dissolved in the water column, where the nitrogen and phosphorus are inorganic nutrients for phytoplankton and macroalgae (Wang et al., 2012). Too high a concentration might trigger toxic algae outbrakes (Reitan, 2020). Fecal particles and uneaten food sinks quickly and gather up in the seafloor sediments. The solid waste may be consumed by detritivores or surrounding fish that eat feed losses in the water column (Wang et al., 2012). Plastic pollution is another central emission issue. It is a challenge due to the large use of plastic material in the industry and its proximity to the aquatic environment. The plastic pollution comes from both waste during operations and microplastic due to the wear of the facility (The Norwegian Government, 2018).

Wild stock interaction:

The wild population of Atlantic salmon in Norway is the world's largest (Johansen et al., 2011). At the same time, Norway is a global leader within salmon farming (FAO, 2020), which has proven to be challenging in terms of wild stock interactions.

Diseases and parasites can uninterruptedly spread to the wild stock through the open cage structures. Enclosing of salmon in high concentrations provides breeding grounds for various pathogens (a bacterium, virus, or other microorganism that can cause disease), and it is proven that the number of microorganisms associated with fish diseases has increased with a growing aquaculture production. This is true for both viral and bacterial diseases (NVI, 2018). The increase in production has also led to an increased availability of susceptible hosts for salmon lice. Thus, the salmon lice at farmed fish creates increased pressure on the wild population, which is as previously introduced the main bottleneck for further expansion of the industry.

Escaped salmon magnifies the problem as it can spread diseases and parasites more actively. Furthermore, escaped salmon introduce the issue of interbreeding between escaped and wild salmon. The escaped salmon can negatively affect the wild salmon populations by means of long-term genetic changes (Forrest et al., 2007). The farmed salmon is usually bred to enhance growth and other characteristics, and may therefore diverge from the genetic material found in the wild population, creating ecological conflicts when escaping occurs. For instance, could aggressive behavior and fast growth of escaped fish give them a competitive advantage towards the native population, resulting in gradually suppression of wild salmon characteristics (Forrest et al., 2007). Preventing fish escapes is the overall motivation in the NYTEK regulation and NS 9415, and the authorities and industry put a lot of effort into mitigating the risk (Yang et al., 2020).

2.4.4 Risk to material assets

This dimension concern the risk related to material assets such as vessels, barges, cages, and the mooring system. If risk related to the structural aspect of a fish farm is not properly controlled, it may have severe economic consequences to the fish farm company. Furthermore, structural failure could lead to increased risk in the other dimensions, for instance could structural damage to the net bag lead to escape. Central threats to structural damage of sea cage are for instance storms/harsh weather, biofouling, and human error during complex operations and use of heavy machinery.

2.4.5 Risk to food safety

The food safety risk dimension is directed to the consumers. Accumulation of toxins in fish meat is the general hazard and concern related to food safety. Strict control through the production is important to ensure the safety of salmon as food. With respect to fish meat, the European Food Safety Authority has focused on the containment level of arsenic, mercury, dioxins, and other dioxin-like compounds (EFSA, 2018). However, a study measuring the containment levels in Norwegian farmed salmon from 1999 to 2011, shows that contaminants of these were all well below the EU regulatory maximum limits (Nøstbakken et al., 2015).

2.5 Risk assessment

This section gives a brief overview of the process of risk assessment. Section 2.2.2 mentioned that NS 9415 refers to NS 5814 in terms of performing risk assessments. Thus, this chapter will use NS 5814 as a basis for documenting the process of risk assessment

NS 5814:2021 has recently been revised and replaces NS 5814:2008. An important change has been to clarify the relation to other standards. In terms of process, the standard refers to the international standard ISO 31000 - Risk management guidelines. ISO 31000 is one of the most generic standards and provides guidelines on how to implement risk management. The process according to ISO 31000 is shown in Figure 9. The workflow is equal for NS 5814 except for two minor customizations: "Scope, Context, Criteria" is called "Framework for the risk assessment", and "Risk identification" is changed to "Identify undesired events". The last difference is made as ISO 31000 covers risk identification in general, whereas NS 5814 aims to identify hazards and threats connected to an undesired event. Otherwise, literature material from the books Rausand and Haugen (2020) and Rausand (1991) have also been applied and functioned as central background material in writing this chapter.

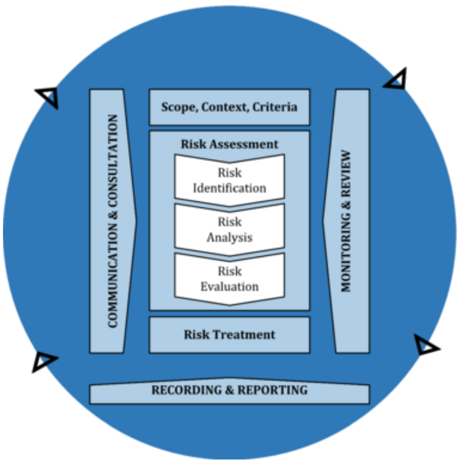

Figure 9: The process of risk assessment according to ISO 31000

ISO 31000 present a guiding principle of risk assessment as the process of risk identification, risk analysis, and risk evaluation, as shown in Figure 9. NS 5814 has adapted the model to additionally include the preliminary work of creating the risk assessment framework, as shown in Figure 9.

Figure 10: The process of risk assessment according to NS 5814

The main objective of any risk assessment is to support decisions. In very general terms, the process of risk assessment systematically studies what may go wrong, describing it and evaluating it against certain criteria. When the risk is evaluated, decisions of whether to reduce risk or not can be taken, and if risk needs to be reduced, which risk reducing action is required.

2.5.1 Definition of risk

The definition of risk is not explicitly defined and opens up for a very wide interpretation of what risk really is. If ten people on the street are asked what risk may mean, they probably give ten different answers, and the interpretation of risk is not much better in the scientific community either (Rausand and Haugen, 2020). For the purpose of the thesis, risk will be addressed and defined as by Rausand and Haugen (2020). It is based upon that we are attempting to envision how the future will turn out if we undertake a certain course of action. Therefore, the definition of risk becomes the combined answer of the three following questions:

1. *What can go wrong?*
2. *What is the likelihood of that happening?*
3. *What are the consequences?*

2.5.2 Framework for the risk assessment

The purpose of this step is to create a customized framework for the intended object, system, and/or activity to be assessed, thus enabling effective and appropriate risk assessment and treatment. According to NS 5814, the framework shall include the following:

- Describe the purpose, requirements, and roughly delimit the study object
- Define and describe values to be protected
- Define risk/evaluation criteria
- Describe object or system to be analyzed
- Select method and justify the chose

2.5.3 Identify undesired events

This part of the risk assessment process aims to identify and describe all threats, hazards, and undesired/hazardous events related to the object or system to be analyzed. In terms of terminology, *Identify undesired events* is the NS 5814 definition, whereas other literature often refers to this step as *Hazard Identification*. Nevertheless, this part aims to answer the first question of the risk definition *What can go wrong?*. The answer to this questions involve consideration of several aspects, and may be answered by a holistic identification of the following (Rausand and Haugen, 2020)

- Hazards - The sources of possible harm
- Initiating events - The starting point in a sequence of events.

- Hazardous/undesired event - The event which has potential to cause harm.
- Enabling events and conditions - Events and conditions that trigger accidents.

In the early stage of hazard and event identification, it's important to get a quick overview of the different hazards and events. Several hazards and events may be identified such as storms, insufficient maintenance, terrorism, etc. (hazards) and fuel gas fire, fish escape, vessel collision (events). An initiating event is the first event in a sequence of events, or more precisely, it is the start of an accident scenario. Accident scenario will be further addressed in the next paragraph. However, the identification and description of threats/hazards, hazardous event, and enabling events/conditions is crucial in order to develop the accident scenarios and further perform the risk analysis.

2.5.4 Risk Analysis

The part of the risk assessment aims to answer the two last questions in the risk definition; *What is the likelihood of that happening?* and *What are the consequences?*. The overall goal is to answer these questions in such a way that it provides input to the coming risk evaluation, and furthermore provide insight to the decisions to be made. The answer to these questions can either be quantitatively, qualitatively, verbally, or visually presented, depending on the analysis requirements and the risk acceptance criteria which the result is going to be evaluated against.

The degree of detail and complexity of the risk analysis will depend on the framework and purpose of the risk assessment. However, it usually involves detailed consideration of likelihood, consequences, risk sources, events and scenarios, uncertainties, controls, and their effectiveness. The bow-tie model is a useful and frequently used model in risk analysis, both for conceptional visualization and for analyzing. The model is shown in Figure 11 and illustrates how hazards can lead to a hazardous event, and furthermore develop into an accident with certain consequences. The hazardous event is placed in the middle of the diagram, with causes and consequences for the event on the left and right side, respectively. The identification of hazards, initiating events, hazardous events, and enabling events and conditions are, as could be seen from the figure, important in order to develop accident scenarios. Accident scenario is a fundamental concept in risk analysis as is describes the "pathway" to an accident. More precisely, it is a potential sequence of events from an initiating event to an end state which will harm one or more assets Rausand and Haugen, 2020. Assets correspond to the previously described *values*.

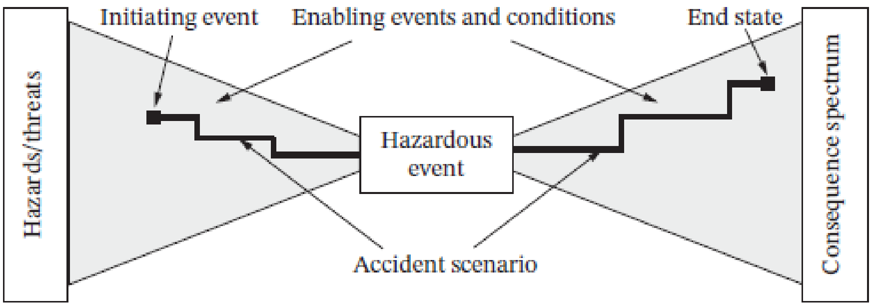

Figure 11: The bow-tie model (Rausand and Haugen, 2020)

Figure 12 illustrates a crane operation in order to discuss the terms related to the bow-tie diagram. The figure shows the relation between a hazard (energy of lifted object), hazardous event (lifting-wire breaks), and consequence (people harmed). Such a hazardous event may have several accident scenarios with different initiating events, enabling events/conditions, and end states. Hypothetically, initiating events might be "impact on wire" or "lift exceed wire WLL (working load limit)", whereas enabling events/conditions could be "harsh weather" or "stressed personnel", and end-events may be "lifted object has fallen on personnel" or "lifted object has fallen on critical equipment". The end events then have associated consequences such as "fatality", "destruction of equipment", "finical lost", "production shutdown" etc. Furthermore, barriers is often implemented in the bow-diagram to illustrate how barrier functions can prevent events in an accident scenario from occurring. The barriers are "obstacles" on the "pathway" leading to the different events, and the bow-tie is a suitable way of distinguishing between proactive and reactive barriers. The proactive barriers are placed before the hazardous event to prevent it from occurring, whereas reactive barriers aim to prevent further escalation and consequences from happening. In case of the crane operation, a proactive barrier before the event "lift exceeds wire WLL" could be the organizational barrier "training of personnel", and a reactive barrier of preventing the consequence of "fatality" could be the technical barrier "Caution signs and ribbons in the lifting area". A bow-tie diagram implemented with barriers is shown in Appendix B.

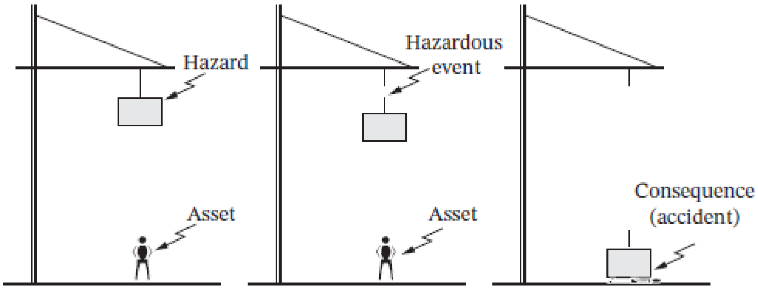

Figure 12: Crane operation (Rausand and Haugen, 2020)

Risk analysis could be complex and addressed in various ways. However, the bow-tie model is a suitable illustration to show the main element and workflow of a risk analysis. The left side of the hazardous event is considered as the region of causal analysis, and usually aims to find and understand the causes which may lead to the hazardous event through an accident scenario, and furthermore determine the frequency of how often the hazardous event occurs. The right side of the hazardous event is the region of consequence analysis, and aims to analyze the development of the accident scenario, from the hazardous event to the end event. It seeks to understand what may influence the accident scenario (external/enabling conditions, barriers), and further determine the frequency/probability of end events and associated consequences for the vulnerable assets. Besides this, barriers strategies and how barriers can stop/mitigate the different accident scenarios are of great importance in both of the analysis regions.

NS 5814 corresponds to this and describes risk analysis as the work of assessing vulnerability in terms of analyzing the accident scenario and efficiency of barriers. Furthermore assessing/estimating likelihood and consequences, and that the risk shall be described and presented as a result of likelihood, consequence, and how vulnerability affects it. The standard also emphasizes the importance of describing uncertainty, which may be related to knowledge-basis, data relevance, and how sensitive the result is against changes in the assumptions of the analysis.

2.5.5 Risk Evaluation

The purpose of risk evaluation is to compare the result of risk analysis with the established risk acceptance criteria (RAC), and decide whether the RAC is met or not. This will further provide support to decisions, where the evaluation may lead to the decision to implement risk reduction measures, review and reconsider RAC, maintain existing risk controls, perform a more detailed risk analysis, or even do nothing further if all RAC are met or risk is decided to be accepted.

Whether the risk is accepted or not may be based on various aspects, such as the cost required for reducing the risk or benefits obtained from accepting the risk. A well-known principle within risk acceptability/tolerability is the ALARP principle. ALARP is an acronym for "as low as reasonably practicable", and implies that a risk is acceptable only if the cost associated with reducing the risk is "grossly disproportionate" with the benefit gained. Thus, the principle aims to reduce the risk level to *as low as reasonably practicable* (Rausand and Haugen, 2020). The ALARP principle is shown in Appendix C. Other well-known methods for evaluating risk are for instance the risk matrices and FN-curves.

2.5.6 The iterative loop of risk management

Figure 13 shows how the risk assessment may be an iterative process, based on Vinnem and Røed (2020)

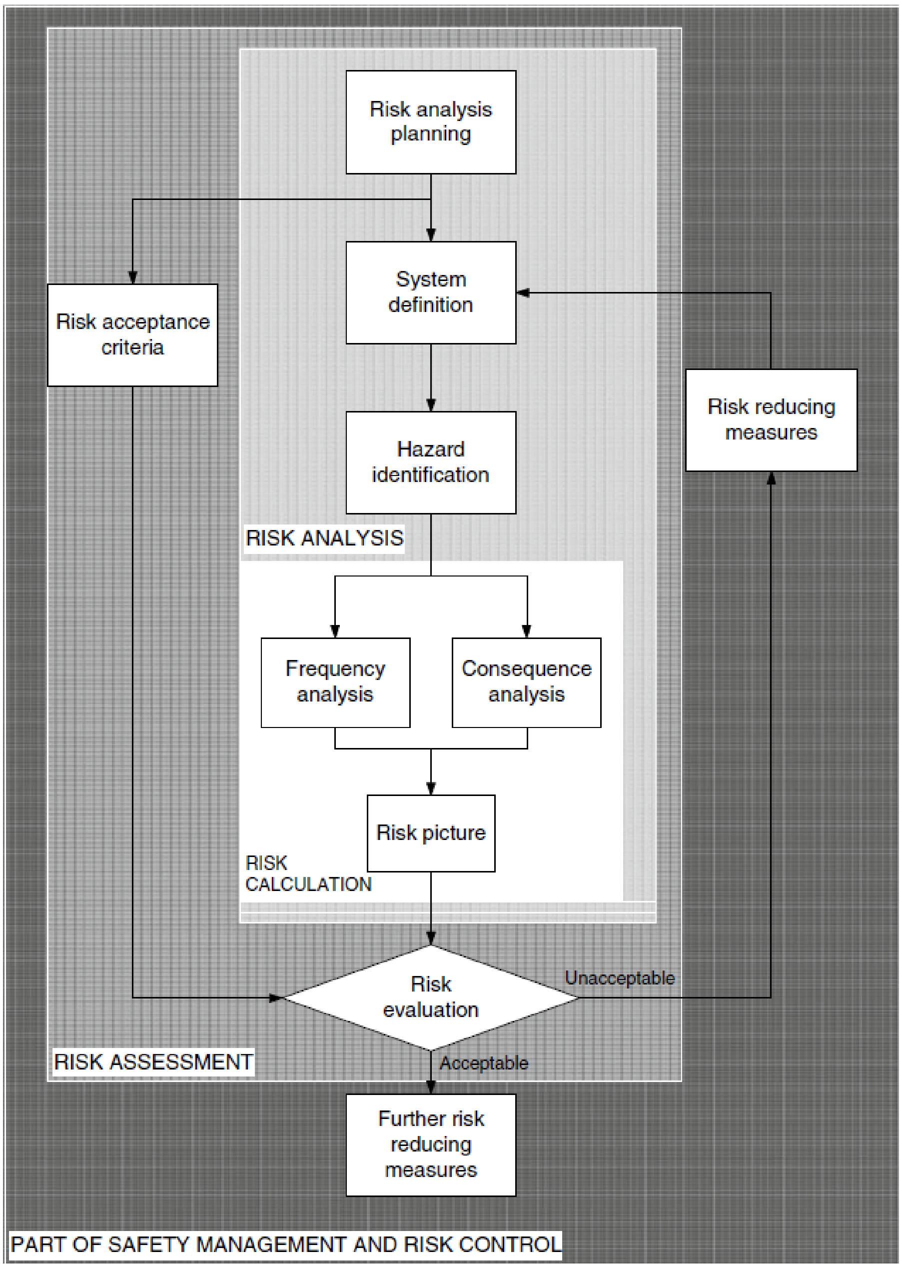

Figure 13: The iterative loop for risk assessment (Vinnem and Røed, 2020)

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3 Methodology

This section covers a description of the change analysis according to Rausand and Haugen (2020) and how the method is applied for the thesis objectives. Section 3.1 is mainly based on method descriptions from the project thesis (Nesje, 2021).

3.1 Change analysis

The Change analysis belongs to the category of hazard identification methods, corresponding to the second step in the risk assessment process shown in Section 2. The method aims to determine the potential effects of some proposed changes or modifications to a system. Changes could influence the risk related to the system and might be a source of accidents. Therefore, it is important to determine the effect and risk impact of changes so that necessary actions can be taken. The change analysis is a comparison study performed by comparing a new (changed) system to a basic (known) system. The system might be a sociotechnical system, a procedure, or a process. And changes can, for instance, be related to policies, changes in activities or operations, technical system configurations, etc. The execution of the analysis might be based on data sources and/or expert judgments. The following list describes the core steps in the method.

1. **Identify the key differences**
   The first step is to identify key differences between the new (changed) and basic (known) system. The term *key difference* is in this method used to indicate a difference between the two systems that can lead to or influence harm. Initially, all differences are identified and listed, where the step consists of a detailed description of both the new and basic system. Differences are identified through comparison and brainstorming and might be grouped/classified.

2. **Evaluate the possible effects of the differences**
   The next step is to evaluate the key difference identified in the previous step, one by one. It should be studied if the difference influences the main system vulnerability and whether or not the difference can lead to harm to any of the values/assets which is to be protected. Both the positive and negative effects on risk should be documented during the evaluation.

3. **Determine the Risk Impacts of the differences**
   This step determines and evaluates the risk impact of every key difference. Possible frequencies and consequences should be identified, and associated risks should be ranked. This step should also propose safeguards, modifications to existing safeguards, or other precautions needed to control the risk introduced by the key differences.

4. **Examine important issues in more detail** One of the limitations of this analysis is that it does not quantify risk in detail. However, the change analysis might reveal central issues which will require further analysis. By highlighting and/or describing these issues, further investigation with other risk assessment tools could be carried out by either the existing or a new study team.

The main limitation of a change analysis is that it requires a thorough knowledge of the systems and risk issues in the basic system. Therefore, it can only be applied efficiently and meaningfully to a system that already has established a risk baseline through experience or previous risk analyses. If knowledge about the basic system and associated risk is available, the change analysis is an efficient and proactive assessment method that systematically explores changes that might introduce risk or contribute to an actual accident.

Appendix D present the analysis workflow according to Rausand and Haugen (2020).

3.2 Adapted workflow and worksheets

This section describes how the change analysis is applied for the purpose of this thesis, as well as presents the customized worksheets. Section 2 has shown the discipline of risk assessment and highlights *NS 5814:2021 - Requirements for risk assessment* as the most relevant guideline when performing risk assessments in Norwegian fish farming. The work in this thesis is therefore guided by the principles described in NS 5814.

Figure 14 presents the core steps of how the thesis's result is derived, and the following method description uses these as headers. The steps are the main steps of a more detailed workflow, presented in Figure 15. The reader is advised to follow the detailed workflow while reading the descriptions, especially if the work is to be replicated.

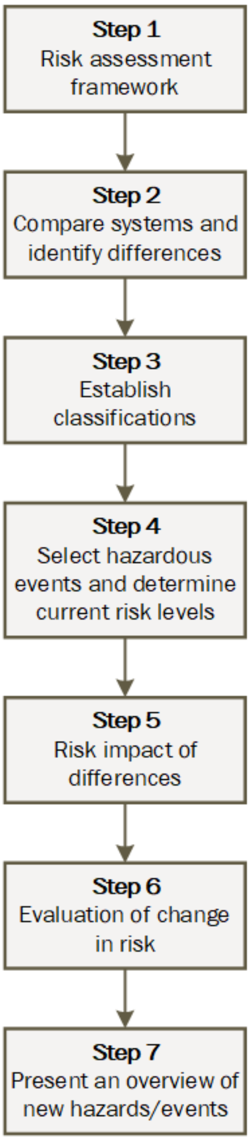


Figure 14: Main work steps

3.2.1 Step 1 - Framework of the risk assessment

This first step is preparation for the risk assessment according to NS 5814 and intends to create a customized framework for the system to be analyzed. The framework shall contain the following.

1. *Purpose, requirements and delimitation*
   The purpose of the risk assessment should describe the needs related to the risk assessment. As mentioned in the literature review, Section 2, the prime objective of a risk assessment is to provide decision support, and therefore, should the needs be expressed as which decisions need to be answered by the risk assessment. Furthermore, the framework should include requirements and guidelines regarding responsibility and roles, knowledge basis, decision-takers, milestones, timeframe, etc. Lastly, the object to be analyzed shall be roughly defined and delimited.

2. *Values*
   Which values and interests to be protected should be identified and explained. This is crucial as values are guiding for which type of consequences that is to be evaluated. Overall values can be structured in a value-hierarchy, where the values are at the top level, followed by the levels of critical functions, objects/systems, and resources that together safeguard the overall values. Examples of values are humans, financial benefits, historical objects/monuments, reputation, a community, material assets (e.g. equipment, infrastructure), or an ecosystem.

3. *Defining risk criteria:*
   The values to be protected should have clear criteria on which type and amount of risk that may be taken and/or not taken. The criteria can, for instance, be functional requirements, technical requirements, or measurable risk indicators. The risk assessment shall be concluded upon evaluation against the risk criteria settled. Thus, these criteria should be determined in cooperation with those who will make decisions based on the evaluated results. The term Risk Acceptance Criteria (RAC) is widely used in this context.

4. *Object-and system description*
   To document, delimit, and understand the object or system to be analyzed is crucial to achieving representative results and safe decisions. The description may include physical, organizational, and administrative traits related to the object. In the context of the change analysis, both the basic (known) and the new (changes) system needs to be described. The differences between the systems are the core element in a change analysis, and components or aspects of the new system that is unchanged should not be described in detail. If doing so, the author might repeat a lot of written material, and the work becomes inefficient. Thus, a short description/introduction of the new system and its primary changes or design intentions may be sufficient.

3.2.2 Step 2 - Compare systems and identify differences

This step intends to produce a list of all differences between the systems. The differences are identified by brainstorming and thorough comparison. The identified difference is numerated, titled, and described. A well-described difference is useful when effects and risk impacts are evaluated. The difference might affect several system vulnerabilities, and a well-described difference could make it easier to reveal all potential effects. Table 1 shows a proposed worksheet for listing differences. It also includes a change mode column, making it convenient for the study team to see if the change introduces a new element/aspect, removes one, or is related to another modification.

Table 1: Worksheet no. 1 - Listing of differences

No.	Title	Change mode			Description
		New	Removed	Other m.	

3.2.3 Step 3 - Establish classifications

This step defines the classification of likelihood and consequences. The classifications are to be used when a key difference influence the system and the risk of the associated events needs to be measured and determined.

In order to measure the risk of hazardous events, the principle of *risk priority number* (RPN) is to be applied in the analysis. RPN is a commonly used metric and is helpful to decision takers when prioritizing risk reduction measures. Events with high RPN values have a larger risk contribution than events with low values. In other words, the metric expresses how much the various events contribute to the "total" risk and enables highlighting of relative importance between events (Rausand and Haugen, 2020).

Therefore, the metric was found convenient for the purpose of this analysis. It would highlight key differences with large risk impacts and help decision-makers prioritize which modifications need redesign, a more detailed analysis, improvements to existing risk controls/barriers, or other risk reduction efforts.

There are two ways of establishing the RPN value, either by adding or multiplying scores on consequence and frequency. According to Rausand and Haugen (2020), the addition rule is the best option when the severity and frequency of an event are determined from logarithmic scales or approximate logarithmic. The addition rule is chosen as the classifications are expected to be on approximate logarithmic scales in this analysis.

$$\mathrm{RPN}_i = L_i + S_i \tag{1}$$

where,

$$L_i = \text{Likelihood according to the frequency of event } i$$

$$S_i = \text{Consequence of event } i \text{ according to its severity}$$

The values defined in the risk assessment framework shall direct the establishment of the consequence classification. It is most likely sufficient with a single scale for frequency, but the consequence classification might need separate scales, depending on the amount and type of values. The scaling of frequency and consequence classes can be quantitative, qualitative, or semi-quantitative, depending on the needs and values to be protected. If a quantitative scale is possible, the classes shall be approximately ten times greater than the preceding ones in order to make the scale logarithmic and appropriate for the addition rule.

3.2.4 Step 4 - Select hazardous events and determine current risk levels

The basic system is usually associated with several hazardous events, some of which might be central motivation factors for the intended modifications. Thus, it is of high interest to understand how the key differences influence and change the risk of these hazardous events. Therefore, this step intends to select one or several hazardous events that can cause harm to the basic system and determine the current risk level. The hazardous events are denoted by E_i.

As mentioned at the start of this methodology chapter, the change analysis is only appropriate if a risk baseline is established for the known system. Thus, when determining the current risk level of the selected hazardous events, it will be most efficient to use expert judgement or previous risk assessment reports as input. Using the classifications from step 3, $\mathrm{RPN}_{i,B}$ shall denote the current risk level of hazardous event i, where B indicates the basic system.

3.2.5 Step 5 - Risk impact of differences

This is the core step of the thesis work. The step uses the list of differences created in step 2 as input and systematically assesses how each described difference influences the risk related to the system, or if it even influences at all. If influencing, i.e., if the difference has a positive or negative effect, it is assigned as a key difference and inserted into the worksheet shown in Table 2. Evaluating effects is carried out through brainstorming and based on expert judgement and/or experience data. As mentioned previously, knowledge about the basic system and associated risk is a crucial prerequisite to assessing the potential effects of differences.

The proposed worksheet is, as shown, divided into two primary columns of positive and negative effects, where the risk contribution of each key difference is to be justified and measured/ranked with RPN. The following list explains the intention of each worksheet column.

- **Key difference**
  The difference (d) that had a positive and/or negative effect is inserted and further considered a *key difference*.
- **Justification**
  With respect to the values and selected hazardous event, the identified effect is described and the risk impact is justified. Description of the effect intends to document identified threats and events related to the key differences, where the particular difference might impact risk by altering the likelihood/consequence of existing causes or events, introducing new hazards/events, or on the other hand, removing existing hazards/events. The associated risk impact is determined through the already established likelihood/consequence classifications. The resulting $\text{RPN}_{i,d}$ is shown in the next column.
- $\mathbf{RPN}_{i,d}$ - Risk contribution of key difference d to hazardous event E_i
- $\mathbf{L}_{i,d}$ - Likelihood of hazardous event E_i to occur due to the effect of key difference d.
- $\mathbf{S}_{i,d}$ - Severity of hazardous event E_i due to effect of key difference d.
- **Hazardous event ($\mathbf{E}_i/\mathbf{E}_i^*$)**
  The analysis aims to determine the risk impact a key difference d has on hazardous event E_i. Thus, only the selected hazardous event is listed in this column. When a difference influence risk of several hazardous events, all relevant events must be listed. If the effect relates to a hazard or cause in the accident scenario of E_i, this will be described and covered in the justification column. However, if a new hazard or event is identified, these should be listed in the column and denoted E_i^*.

Table 2: Worksheet no. 2 - Risk influence of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN**$_{i,d}$	**L**$_{i,d}$	**S**$_{i,d}$	**Hazardous event (E**$_i$**/E**$_i^*$**)**	**Justification**	**RPN**$_{i,d}$	**L**$_{i,d}$	**S**$_{i,d}$	**Hazardous event (E**$_i$**/E**$_i^*$**)**

3.2.6 Step 6 - Evaluation of change in risk

In this step, the change in risk of a selected hazardous event E_i is to be evaluated. All relevant key differences are then assembled into the proposed worksheet in Table 3. The worksheet intends to provide an overview of all key differences that have contributed to change in the risk picture of hazardous event E_i. The template also has a column where possible risk reduction measures can be suggested and numerated.

Table 3: Overview of key differences influencing E_i and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	$RPN_{i,d}$	No.	
x			Neg.		1	Proposed measure no. 1
x			Pos.			
			$RPN_{i,A}$:	x		

The step also involves a calculation of $RPN_{i,A}$, which is the average risk impact of all key differences, as indicated below. Further, $\Delta Risk_i$ is to be calculated based on the average impact and current risk level of hazardous event E_i, and is to be used as a numerical indicator of overall change in risk. It is crucial to keep in mind that $RPN_{i,A}$ and $\Delta Risk_i$ are not a presentation of the change in risk level by going from a basic system to the new system. There could still be hazards/events in the new system that have not been affected by the planned modifications, and therefore is $RPN_{i,A}$ not representative as a new risk level. Thus, $RPN_{i,A}$ and $\Delta Risk_i$ are only numerical indicators of overall change in the risk picture.

$$\Delta \mathrm{Risk}_i = RPN_{i,A} - RPN_{i,B} \tag{2}$$

where,

$$RPN_{i,A} = \frac{1}{n}\sum_{k=1}^{n}[RPN_{i,d}]_k = \text{Average risk impact of key differences} \tag{3}$$

Lastly, for each hazardous event E_i, the result shall be discussed. Presenting and discussing the result shall involve highlighting key differences that had a large influence on risk, important risk reduction measures, and discussion related to the uncertainty of the results. Each key difference changes the risk picture of the particular hazardous event and should have the primary attention. However, it is of high interest to determine if the overall change in risk - that is, how all relevant key differences together have changed the risk of hazardous event E_i. The conclusion of overall change in risk shall state if the change is positive, negative, or equal, and shall be based on a discussion of the various risk impacts and associated uncertainty.

The result of the analysis is the basis for decision-making. The result of how a key difference has influenced risk will bring decision support to whether the intended modification can be preserved, must be re-designed, examined in more detail, implement a risk reduction measure, or other decisions. An important part of establishing a good decision basis is to tell the decision-makers how trustful the result is, in other words, express the uncertainty of the result. NS 5814 also emphasizes the importance of describing uncertainty. Provided information, available data, knowledge basis, and to what degree changes in assumptions and boundary conditions could influence the results are important factors when assessing uncertainty.

3.2.7 Step 7 - Overview of new hazards/events

The last step intends to provide an overview of the hazards and hazardous events introduced by the new system. These events, denoted by E_i^* in the analysis worksheet (Table 2), are already assessed and discussed in the preceding steps. Thus, the step only intends to give a clear repetition/overview of new hazardous events, associated risks, risk reduction measures, and responsible key differences.

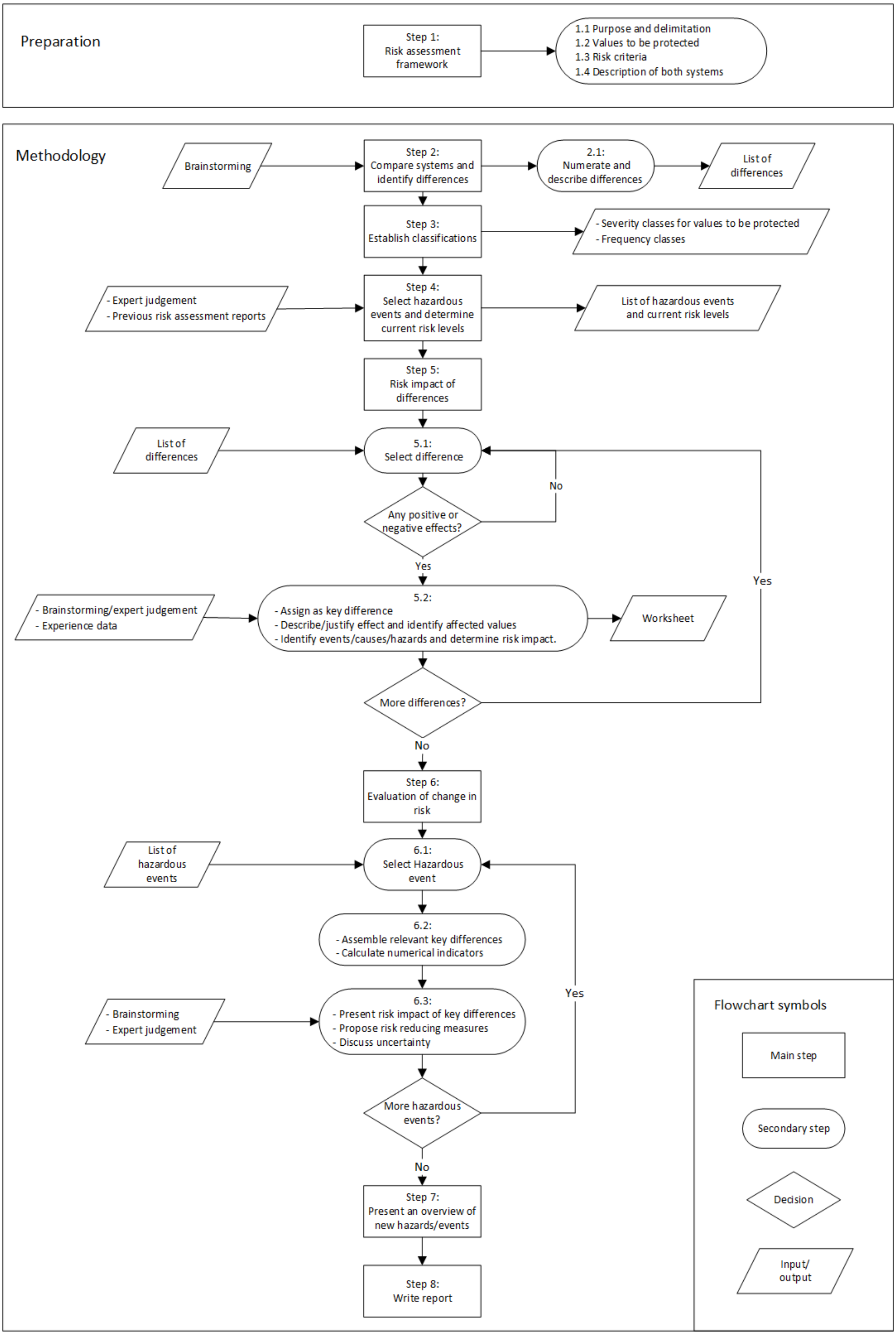


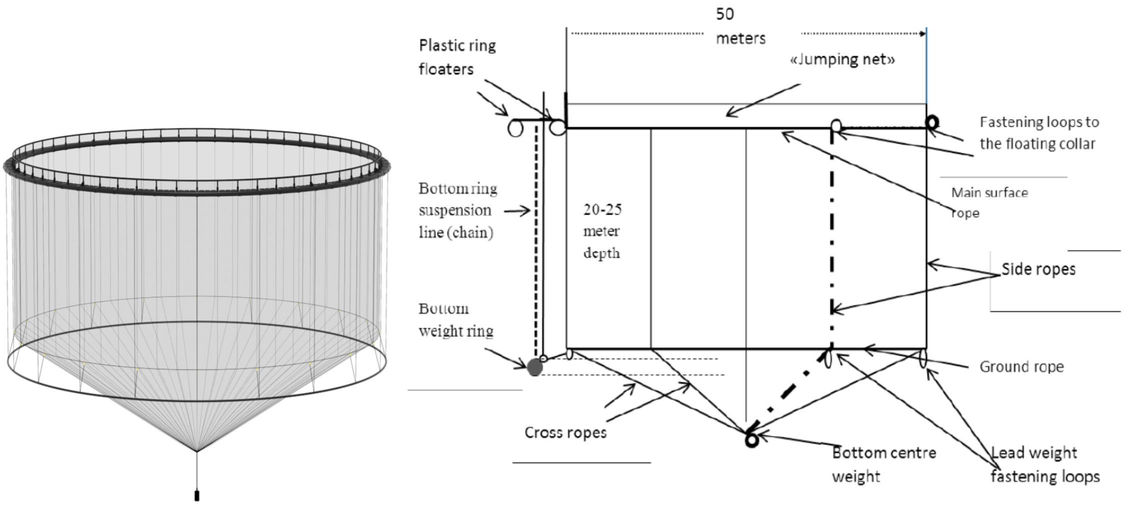
Figure 15: Detailed workflow

4 The basic system - Conventional sea cage

This section defines the conventional sea cage that applies to this analysis. The conventional sea cage is the basis for comparison and the section describing both the technical and operational aspects of the system. Furthermore, the section defines the system boundary, which will be the same for the basic and the new system.

4.1 Overview

There are numerous configurations for sea cages in Norwegian aquaculture, varying in size and design. Some cages are made out of steel and are square-shaped, and there are several types of netting bag systems. However, today's most used sea cage configuration is floating circular net cages made out of high-density polyethylene (HDPE) plastic collars, equipped with a cylindrical net and bottom weight ring. An overview of the sea cage is shown in Figure 16 and could be considered an "industry standard" and conventional in Norwegian Aquaculture. The enclosure can house a maximum of 200 000 salmon individuals, where the maximum allowable stocking density of fish is 25kg/m^3 (Ministry of Trade, Industry and Fisheries, 2021).



(a) Illustration

(b) Dimensions and overview

Figure 16: HDPE collar cage w/ cylinder net and bottom ring weight system (Hatlem and Kvamme, 2016)

The sea cage is designed by the principle of using buoyancy and weights to hold the volume and shape of the structure against environmental forces. Through the use of circular plastic collars, the framework is quite flexible and follows the wave motions, and forces will be more evenly distributed compared to a square shape. The cage system is sometimes referred to as a gravity cage (Lekang, 2020). A more detailed description of the system functionality and corresponding components are covered in Section 4.3.

The system description is based on the principle and terms defined in NS 9415:2021. The new revision clearly defines and distinguishes between main components and auxiliary components and emphasises the importance of functions. Based on this, Table 4 and Table 5 gives an overview of the conventional sea cage in accordance with NS 9415. This is just an overview before going into details of the system and defining system boundaries, and it needs to be mentioned that there are components not listed. It is also worth mentioning that this chapter does not describe the different terms and principles of NS 9515:2021. The terms are only applied, with the intention to form this chapter as technically precise and consistent as possible. The reader is advised to see the standard for descriptions of terms.

Main components

NS 9415:2021	Function	Conventional sea cage.
Floater	Ensure adequate buoyancy and stability	HDPE plastic collars 157m/160m (circumference)
Enclosure	Keep the fish in place	Circular straight-walled net bag

Table 4: Main components according to NS 9415

Note: NS 9415 also defines *Mooring-system* and *Barge* as main components, but these systems are not a part of the analysis. This is shown in Section 4.2, which delimits the study object through a system boundary.

Auxiliary equipment

Permanent auxiliary equipment	Temporary auxiliary equipment
Bottom weight ring (expansion system), deadfish removal system, feed system (spreader and plastic pipes), camera and winch, lice skirt, bird net system(net and rods or float), hideouts, electrical cabinet, sensors.	Delousing tarpaulin, pearl-line, ROV, net-washers, O_2 system, sensors, seine net, testing of demo-equipment, weights around suction pipe inlet used during delivery etc.

Table 5: Auxiliary equipment according to NS 9415

Which auxiliary equipment that is applied varies a lot from farm to farm and depends on the farm's needs and preferences of suppliers. Nevertheless, Table 5 gives an overview. The configuration of auxiliary equipment which applies in this analysis is established in Section 4.3

4.2 System boundary and interfaces

A part of the risk assessment framework is to delimit the study object. This is an important limitation that shall define which components are part of the analysis and which are not. A helpful approach for this purpose is to establish a system boundary around the system to be studied. The system boundary created for the sea cage is shown in Figure 17, where the sea cage is broken down into main components and auxiliary equipment. Technical interfaces are denoted by either a green or yellow plate, depending on if the interface composes two main components or is linked to auxiliary equipment. The internal system breakdown of the sea cage is carried out in the next section.

- **External technical interfaces (EI) at the system boundary**
  The system boundary is set at some distance from the floating collar to include the vessels and activities which take place around the cage.
  - EI.1 - Bridles. The system boundary intersects at the midpoint of the bridles, i.e. halfway down from the floating collar fastening point. There are 12 bridles.
  - EI.2 - Air pipe. The system boundary intersects the air pipe 10 meters from the floating collar.
  - EI.3 - Feeding pipe. The system boundary intersects the feeding pipe 10 meters from the floating collar.
  - EI.4 - Power cable. The system boundary intersects the power cable 10 meters from the floating collar.
- **Inputs**
  The input to the sea cage is classified into two groups:
  - Wanted inputs:
    The energy and material required for the farmers to perform their daily husbandry practice.

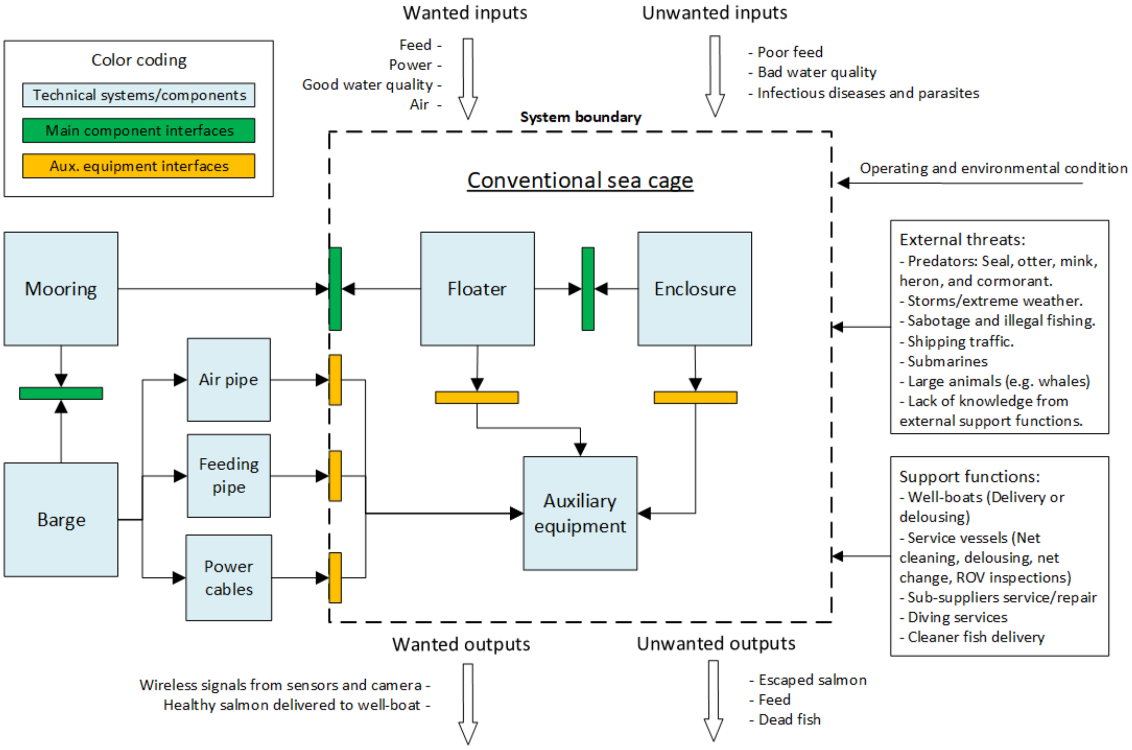


Figure 17: System boundary and interfaces

- Unwanted inputs: Some inputs might have conditions or variations that are unwanted. For the sea cage, this might be poor quality of feed and water quality, as well as the water being a carrier of infectious disease and parasites.

- **Outputs**
  The output of the sea cage is classified into two groups:

  - Wanted outputs: The desired output reflects the result of the overall system function, that is, to farm a healthy salmon. Therefore, the wanted output is a healthy salmon delivered to the well-boat, as well as a successful transition of signals for environmental and camera monitoring.
  - Unwanted inputs: The most important are escaped fish, uneaten feed and dead fish.

- **Operating condition**
  The main operating condition is explained in Section 4.4.1 - *Normal operation*. In terms of environment, the operating condition varies a lot among the approximately 1000 sea farms in Norwegian aquaculture (Directorate of Fisheries, 2022a). Exposure to waves, wind, and current is very site-specific. Some farm sites are located deep into the fjords, whereas others are placed along the shore in almost open waters. The environmental condition determined for this analysis is a wave exposure of H_s=2m (return period of 50 years), which ScaleAQ confirms as a fairly conventional significant wave height (H_s). With respect to a maximum current velocity of 0.85 m/s for medium-sized salmon (Hvas et al., 2019), the current exposure is settled to moderate.

- **External threats**
  The conventional sea cage is vulnerable to several external threats, as the list in Figure 17 indicates. The threats might directly impact the sea cage, or they may affect the system boundary inputs. Distinguishing between threat and unwanted input is not always easy, and it could, for instance, be argued that parasites are an external threat.

- **Support function**
  Figure 17 shows support functions that traditionally are needed throughout a production cycle.

4.3 System breakdown

This section organizes the sea cage into a hierarchical structure, where the cage is divided into several subsystems and components. Each system/component is assigned a unique tag number. Figure 18 shows the sea cage breakdown, followed by descriptions.

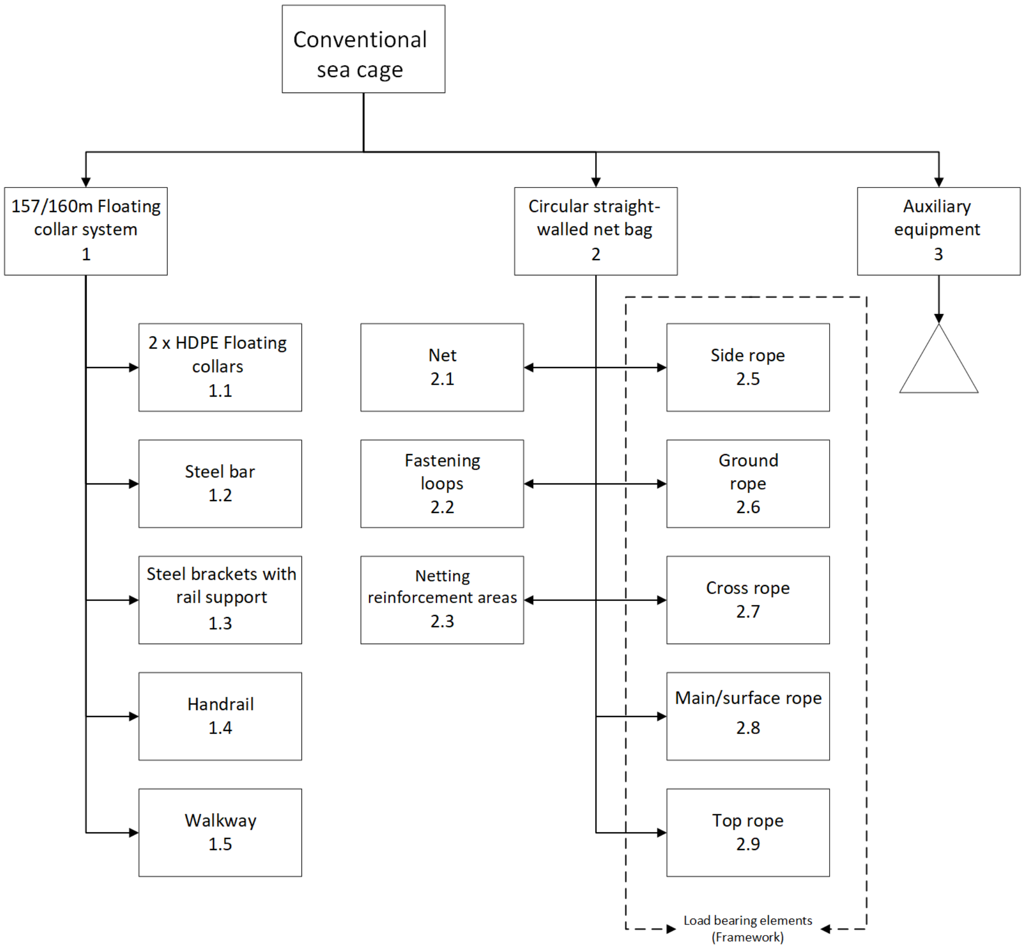


Figure 18: System breakdown

4.3.1 157m Floating collar system

The floating collar system and corresponding tag numbers are shown in Figure 19. The floating collar system diameter is 50m. Thus, 157m indicates the circumference. The system composes one inner and outer HDPE collar (1.1). These are integrated into 60 steel brackets (1.3) evenly distributed around the collar system. The steel brackets and the steel bar (1.2) form the skeleton of the collar system. The bridles are fastened to twelve of the steel brackets, and the major environmental forces acting on the sea cage are absorbed in this load-bearing framework. The steel bar encircles the whole cage and is hidden underneath the walkway (1.5). The steel brackets also support the handrail (1.4). The handrail and the floating collars are not fixed to the steel structure. This ensures relative motions between the plastic collars and the load-bearing steel structure and intends to protect the collars from large forces.

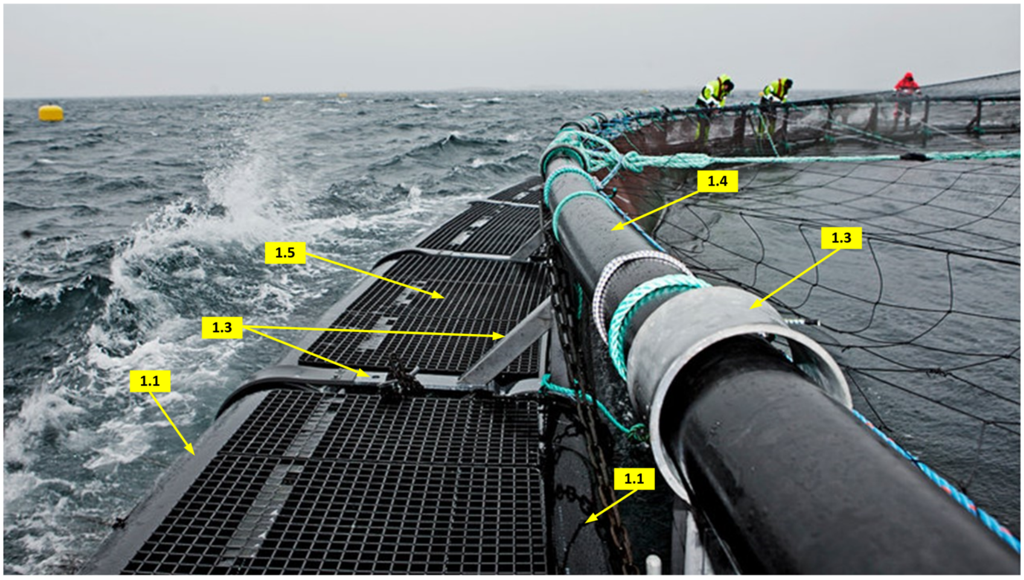


Figure 19: Floating collar system corresponding to Figure 18. Adapted from Hallingplast (n.d.)

4.3.2 Circular straight walled net bag

Since NS 9415 is a copyright-protected document, the net bag illustration can not be attached to this thesis. Thus, the net bag illustration in Figure 16b is used as a reference for this description. Apart from some components, the drawing is sufficient and mainly uses the same terms as the standard. The system breakdown hierarchy denotes which ropes in the net bag are load-bearing, which together creates the framework of the net bag. The top rope (2.9) is, as the name implies, the uppermost circular rope. The top rope is attached to the handrail, and together with the main rope (2.8), they frame the jumping net. Further, it should be mentioned that fastening loops (2.2) on the ground rope and main rope are load-bearing elements, but loops at the top rope are not. Side ropes (2.5) are vertical load-bearing ropes, and not all are connected to the cross ropes (2.7), which are load-bearing in the conical part. There are usually 60 side ropes, where 20 of them are connected to a cross rope. These 20 are, according to NS 9415, named lifting ropes. The lifting ropes carry the whole weight when the net bag is lifted out of water. Netting reinforcement areas are implemented in interfaces that pose a risk to wear and fish escape. Such places are by the water surface, the ground rope, and the bottom of the net bag.

Netting characteristics

Two central netting characteristics are *hanging ratio* (E) and *solidity ratio* (S_n). These are important as they are decisive for the environmental condition inside the net bag, as well as the resulting forces acting upon the net bag.

The hanging ratio expresses how the net is shaped and stretched, as shown in Figure 20. More specifically, it refers to the ratio of the length of the rope to the stretched length of netting attached to the rope, as indicated in Equation 4 (He et al., 2021). The typical E for net bags is 0.6-0.9 (Lekang, 2020). When the net is stretched, it is also possible to measure the mesh size, that is, the distance between two knots of an outstretched net. Mesh opening is the inner distance between the knots (Standard Norge, 2021).

$$E = \frac{L}{Lo} = \frac{\text{Length of rope on which a net panel is mounted } (L)}{\text{Length of stretched netting hung on the rope (Lo)}} \tag{4}$$

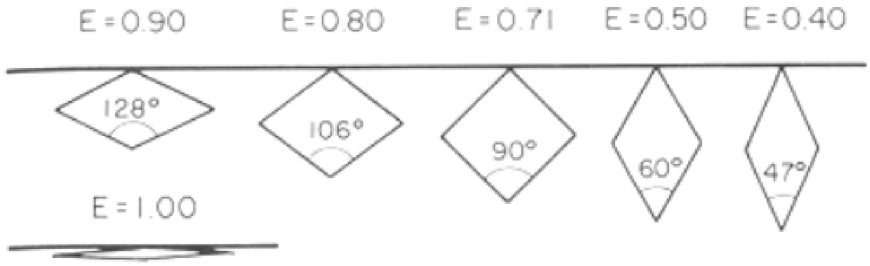


Figure 20: Shape of the mesh at different hanging ratio E. (FAO, n.d.[a])

The solidity ratio S_n is a measure of how "compact" the net is. More precisely, it expresses the relationship between the area covered by netting and the total area. The solidity is an important measure as it is decisive for the hydrodynamic loads acting on the net, as well as it impacts water exchange in the cage. NS 9415 defines solidity for a square-shaped mesh by Equation 5. Biofouling can dramatically increase solidity.

$$S_n = \frac{2 \cdot t \cdot M_S + t^2 + D^2 - 2\sqrt{2} \cdot D \cdot t}{M_S^2} \tag{5}$$

where,

M_s	Mesh bar (length of twine between two adjacent knots)
t	Twine-thickness
D	Knot-diameter

4.3.3 Auxiliary equipment

The continuation of the system breakdown in terms of auxiliary equipment is shown in Figure 21. The breakdown and the following table establish the auxiliary equipment that will apply in this analysis. It is a considerable variation of sub-suppliers and equipment in the industry, but the following configuration is considered fairly conventional. Figure 21 shows the physical decomposition of the various auxiliary equipment, whereas the table provides descriptions of their purpose or functionality.

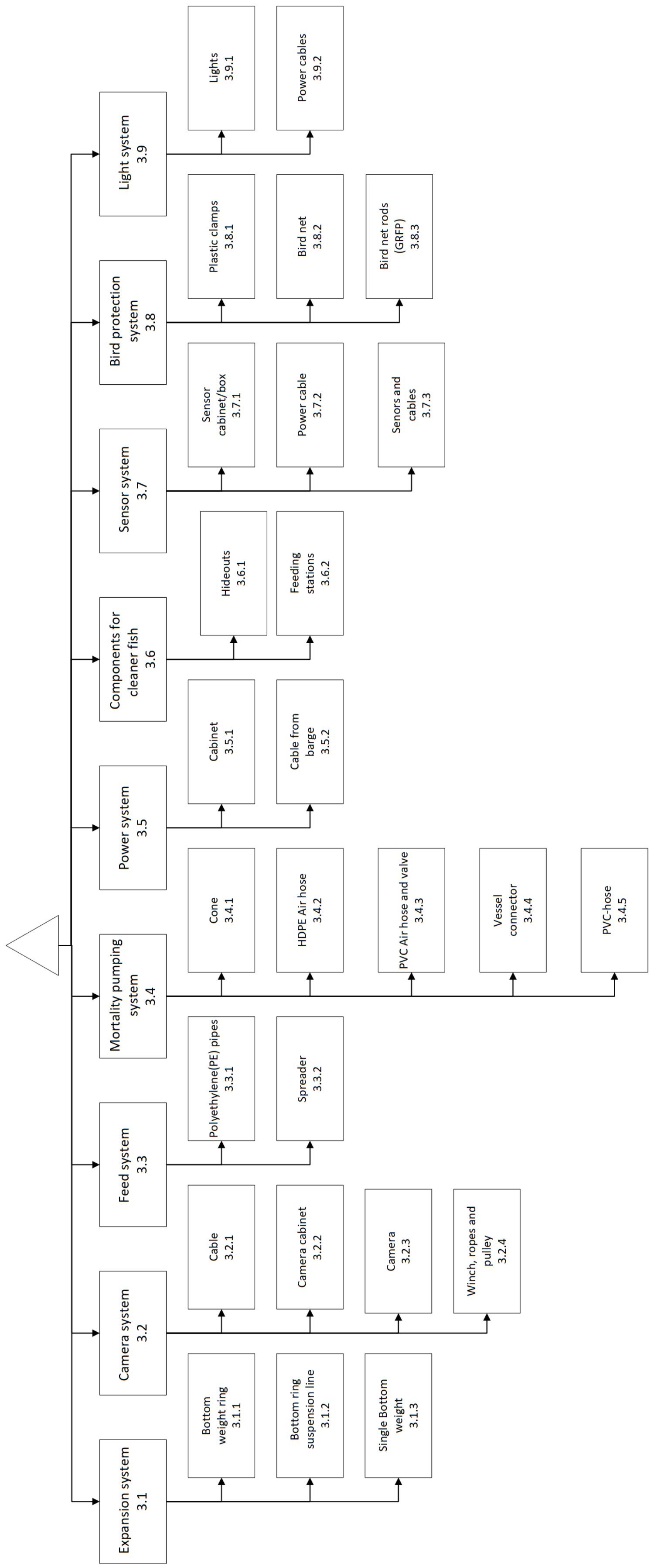


Figure 21: System breakdown continued

Table 6: Auxiliary equipment

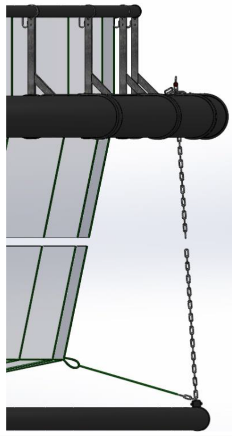
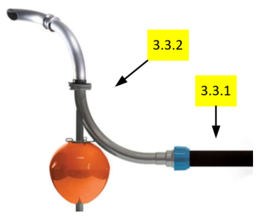
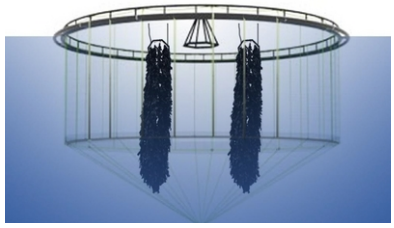
Tag no.	Description and illustrations	
3.1	**Expansion system:** The purpose of the expansion system is to ensure the three-dimensional form of the net bag. The sub-system intends to maintain the required volume and stocking density during strong current conditions and compose two main weights. The bottom weight ring (3.1.1) is suspended in the floating collar by the suspension line (3.1.2) (made out of chains) and fastened to the ground rope. The ring is made out of HDPE and filled with weights to increase density, typically 40-70 kg/m (Lekang, 2020). Optimal weight and stiffness of the ring are crucial for maintaining the cylindrical shape of the net bag. The chosen suspension type is shown in the figure. An independent secondary weight (3.1.3) is suspended in the bottom centre and stretches the conical part. This weight is typically made out of large chains or concrete blocks. Source of the figure: ScaleAQ (2014).	
3.2	**Camera system:** The purpose of the camera system is to monitor the feeding activity inside the cage environment. The camera system consists of a ropeway and a winch (3.2.4) that enable dynamic positioning of the camera (3.2.3) in both surge and heavy directions. In other words, the camera can follow the feed activity along two axes, across the cage and downwards. Thus, the camera can also be descended to control the amount of dead fish. Further, the camera system composes a cable and cabinet for transferring wireless signals to the barge. The system is powered by a power cabinet (3.5.1). Source of the figures: ScaleAQ (n.d.[b]).	 
3.3	**Feed system:** The purpose of the feed system is to transfer and spread feed pellets evenly around the cage. The pellets are transported through a feeding pipe (3.3.1) by pressurized air from the barge, which finally enters the center-positioned spreader (3.3.2). The spreader rotates due to the airflow and disperses the pellets evenly around the cage. Source of the figure: Akvagroup (n.d.).	
3.4	**Mortality system:** The purpose of the mortality system is to collect and transport dead fish out of the sea cage environment. When the fish dies, it sinks to the bottom of the net bag, where the cone (3.4.1) is installed. A flexible PVC hose (3.4.5) is mounted to the top of the cone at one end and the vessel connector (3.4.4) at the opposite end. The vessel connector is attached to the handrail. These three units create a sealed tube that extends from the bottom of the cage to the surface. After the working vessel is connected to the vessel connector, pressurized air is sent down to the cone through a valve and an air hose (3.4.3 - red/blue in the figure). When air enters the cone, it will rise through the sealed PVC hose and create a vacuum that forces the dead fish into the vessel. Compressed air is sent from the barge and enters the sea cage through a stiffer HDPE air pipe (3.4.2). This pipe corresponds to external interface no.2 (EI.2). Source of the figure: iLaks (2014)	

Table 6 continued on next page

Table 6: Auxiliary equipment

Tag no.	Description and illustrations
3.5	**Power system** The purpose of the power system is to supply the camera system (3.2), sensor system (3.7), and light system (3.9) with electrical power. A power cabinet (3.5.1) is mounted to an appropriate steel bracket (1.3) and supplied from the barge by a cable (3.5.2). This electrical cable corresponds to external interface no. 4
3.6	**Components for cleaner fish:** The hide-outs (3.6.1) are sheltering and resting areas for the cleaner fish. These are important elements as they simulate the cleaner fish's natural habitat, which is in kelp forests in shallow waters (IMR, 2021a). Feeding stations (3.5.2) shall provide the cleaner fish with feed pellets and are installed on the handrail and/or as small feeding bags, both close to the hide-outs. The hide-outs should be strategically placed to obtain a high frequency of passing salmon. This will increase delousing efficiency, but at the same time, the hide-outs must not interfere with feeding salmon and should be sufficiently close to the feeding stations. Source of the figure: Kyst (2013) 
3.7	**Sensor system:** The purpose of the sensors is to monitor the water quality in the cage environment. Monitoring of water quality parameters of oxygen and temperature is required by Ministry of Trade, Industry and Fisheries (2021).
3.8	**Bird protection system:** The purpose of the bird protection system is to safeguard the fish from flying predators and prevent them from eating the pellets. Examples of predators are herons, cormorants, and seagulls. The chosen protection system uses glass-fiber reinforced polyester (GFRP) rods (3.8.3) mounted to each steel bracket (1.3) by plastic clamps (3.8.1), which together hold and tension the bird net (3.8.2). Source of the figure: Mørenot (n.d.) 
3.9	**Light system:** The purpose of using lights in the sea cage is to partly control the vertical distribution of the school, as well as lights can reduce the amount of sexually mature salmon. Controlling the vertical behaviour of the fish may also increase growth and reduce the lice infestation. Source of the figure: ScaleAQ (n.d.[a]) 

4.3.4 Internal interfaces

This section covers an overview of the various interaction points between main components and between main components and auxiliary equipment. External interfaces (EI) have previously been presented. Thus this section covers the technical interfaces within the system boundary. To present the internal interfaces (II) in the basic system is important as modifications might be directed to the fastening or interaction point between two components.

The main components and auxiliary equipment are, to a large degree, interacted through fastening points. Therefore, it is important to focus on proper adaptation during design to avoid adverse relative motions or exceeded yield strength in adjacent components or the fastening itself. NS 9415 also emphasizes the importance of ensuring safe interaction between components. Figure 22 and Table 7 present the various equipment that works together and how they are fastened. As the figure indicates, the presentation distinguishes between interactions between main components (blue) and between main components and auxiliary equipment (yellow). The overview clearly shows that most auxiliary equipments are fastened to the handrail by ropes. An up-scaled version of Figure 22 is shown in Appendix E.

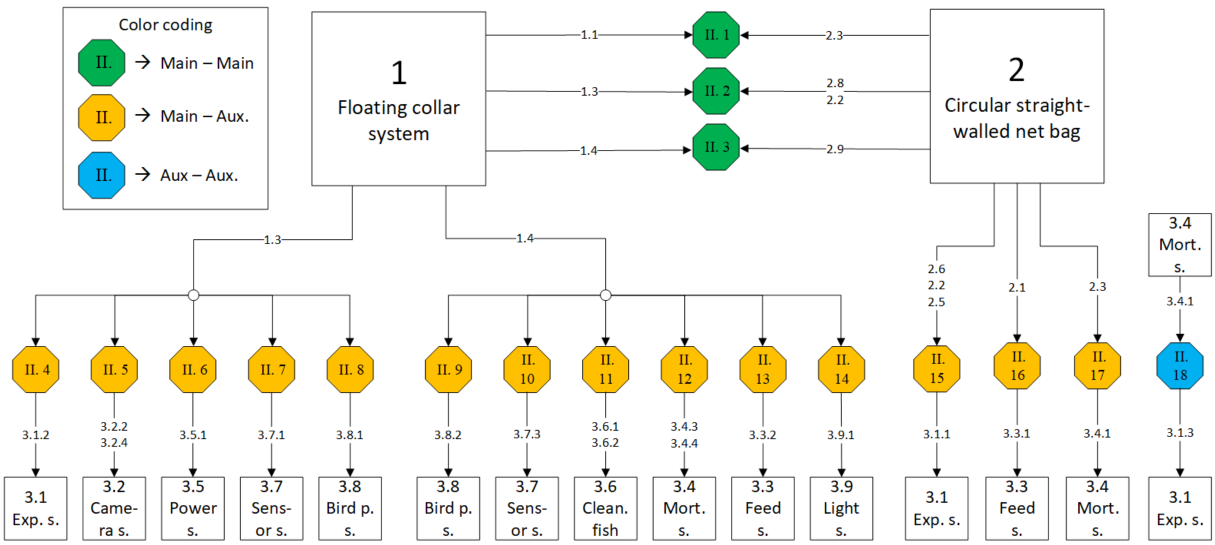


Figure 22: Internal interfaces

Table 7: Internal interfaces

First level	Second level	Tag	Interface	Tag	Second level	First level
Floating collar system	Collar	1.1	II.1 Physical contact	2.3	Netting reinfor. field	Net bag
Floating collar system	Steel bracket	1.3	II.2 Ropes	2.2 2.8	Fastening loops Main rope	Net bag
Floating collar system	Hand rail	1.4	II.3 Ropes	2.9	Top rope	Net bag
Floating collar system	Steel bracket	1.3	II.4 Steel splint	3.1.2	Chain suspension line	Expansion system
Floating collar system	Steel bracket	1.3	II.5 Bolts	3.2.2 3.2.4	Cabinet Winch	Camera system
Floating collar system	Steel bracket	1.3	II.6 Bolts	3.5.1	Cabinet	Power system

Table 7 continued on next page

Table 7: Internal interfaces

First level	Second level	Tag	Interface	Tag	Second level	First level
Floating collar system	Steel bracket	1.3	II.7 Bolts	3.7.1	Cabinet	Sensor system
Floating collar system	Steel bracket	1.3	II.8 Bolts	3.8.1	Plastic clamps	Bird protection system
Floating collar system	Handrail	1.4	II.9 Ropes	3.8.2	Bird net	Bird protection system
Floating collar system	Handrail	1.4	II.10 Ropes	3.7.3	Sensors	Sensor system
Floating collar system	Handrail	1.4	II.11 Ropes	3.6.1	Hide-outs	Cleaner fish components
Floating collar system	Handrail	1.4	II.11 Bolts	3.6.2	Feeding stations	Cleaner fish components
Floating collar system	Handrail	1.4	II.12 Ropes	3.4.4	Vessel connector	Mortality system
Floating collar system	Handrail	1.4	II.12 Tape/Rope	3.4.3	PVC Air hose and valve	Mortality system
Floating collar system	Handrail	1.4	II.13 Ropes	3.3.2	Spreader	Feed system
Floating collar system	Handrail	1.4	II.14 Ropes	3.9.1	Lights	Light system
Net bag	Ground rope Fastening loops	2.6 2.2	II.16 Ropes	3.1.1	Bottom weight ring	Expansion system
Net bag	Netting	2.1	II.16 Net-entry ring	3.3.1	Feeding pipes	Feeding system
Net bag	Netting reinfor. field	2.3	II.17 Physical contact	3.4.1	Cone	Mortality system
Mortality system	Cone	3.4.1	II.18 Ropes	3.1.3	Single bottom weight	Expansion system

4.4 Operational aspect

Operating a sea-based farming facility involves numerous operations, varying in extent and complexity. The operation is mainly managed by the fish farming company itself, with their own production strategies and policies. However, some operations are required by regulatory authorities, such as regular lice counting (Ministry of Trade, Industry and Fisheries, 2016b). The governing regulation for those operating a farm is the *Regulation on the Operation of Aquaculture Production Sites* (Ministry of Trade, Industry and Fisheries, 2021). The production and feeding regimes vary between companies, and it is not an objective of this thesis to study the operational context in very much detail. Thus, this section intends to give a concise description of the main operations in traditional sea-based farming and their core elements. The section divides the operational part into two groups: Normal operation and on-demand operations.

4.4.1 Normal operation

Normal operation comprises the daily and routine husbandry practices at the site. Normal operation, or farming, is all about growing a healthy salmon through efficient feeding and good fish welfare, consequently resulting in profitable production. At the same time, the farmers shall focus on ensuring occupational safety and avoiding adverse effects on the surrounding environment. The following chapter describes the various daily and routine operations related to the sea cage.

Working vessel

Many of the following operations are carried out by designated working vessels. The vessels have typical lengths of 8-15m and belong to the fish farm. A typical working vessel is shown in Appendix G. The vessel is usually equipped with capstans and a crane, which are essential tools for the fish farmers and are used almost on a daily basis, both for routine and non-routine operations (equipment installation or removal, repair, on-demand operations, etc.).

Feeding and feed control:

Feeding is usually performed by hand during the first weeks. The salmon is at this stage categorized as smolt and is unfamiliar with the environment in the sea cage. It needs some time to adapt, particularly to the feeding system (spreader). Hand-feeding is then performed by throwing feed from the walkway, as shown in Figure 23. The fluctuating and new environment is stressful for the fish, and some individuals might stop eating or choose a zooplankton diet (lower growth and higher parasite infection risk). These individuals will eventually be smaller and outcompeted for food by the others, and the fish are referred to as "loser fish" (emaciated fish, described in "Fish welfare monitoring"). By manual feeding, the likelihood of satiating all smolts will increase and thus reducing the amount of "loser" fish. Furthermore, the fish will typically gather and position themselves against the current direction, and the farmers must actively seek the fish when feeding. Although the biomass is small at this point, hand feeding is time demanding and might have negative effects by delaying other tasks or insufficient feeding in case of harsh weather. At the same time, in this vulnerable stage of the production cycle, much time is spent on the cage and is positive in terms of fish welfare monitoring. Overall, targeted hand-feeding and proximity to the fish are essential for a healthy transition from freshwater to the sea cages, ensuring optimum adaption and as few "losers" as possible.

Figure 23: Hand-feeding (Laksefakta, 2021)

After a while, the feeding is performed from the barge in more safe working conditions. Here, control is obtained by surface and/or sub-surface cameras. The feeding is then performed by a fish farmer, which controls the feed flow based on the behaviour of the salmon, seen through the cameras. If the activity underneath the spreader decreases and feed pellets sinks to the lower part of the net bag, the salmon are getting satiated, and the feed flow must be reduced. In other words, uneaten pellets and fish behaviour is used as the main indicators during feeding. Furthermore, water quality parameters (temp., O_2, current etc.) and feeding data from previous days are also decisive for the farmers feeding strategies. Temperature and oxygen monitored through the sensors are important input parameters as they influence the appetite and growth (Noble et al., 2018). Typically, the growth and oxygen need for the salmon decrease in the winter months when the temperature is lower. The importance of temperature and oxygen during normal operation is further discussed in *Fish welfare monitoring*. Furthermore, a disease outbreak might also reduce appetite. Generally, the appetite may vary a lot throughout the day and between days. It is therefore difficult to feed daily servings of predefined amounts, and feeding should be a prioritized task in the daily operation at the farm.

Overall, feeding aims to obtain desired growth rates at the lowest possible cost. Feed is a large operational cost for the farmers, and fish that grows fast usually has a low feed conversion rate (FCR) (MOWI, 2015). FCR describes how efficient the fish utilize the feed and is a central measure in the feeding practice. It tells us how many kilograms of feed the salmon needs to grow one kilogram: FCR=(feed given [kg])/(biomass increase [kg]). Figure 24 shows how effective the cultivation of salmon is compared to other protein productions. Another central measure is specific growth rate (SGR), which expresses the percentage increase in fish weight per day (Skretting, 2022). Input parameters are start- and end weight (or biomass) and the number of days between the start and end, as indicated below.

$$SGR = \left(\left(\frac{\text{End weight}}{\text{Start weight}} \right)^{(1/\text{ days })} - 1 \right) \cdot 100 \tag{6}$$

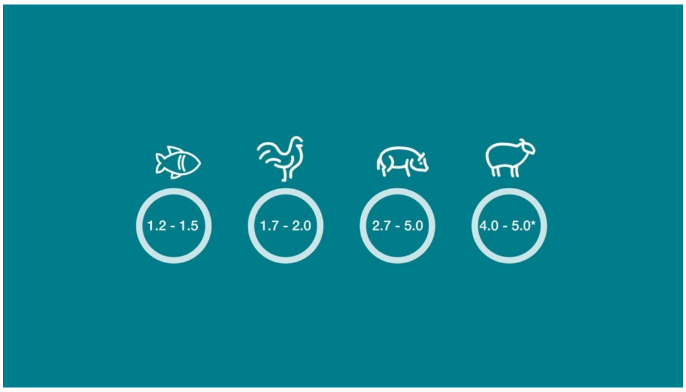


Figure 24: Various FCR's according to the feed company Skretting (2022)

Local feeding from barge has been the traditional practice and is still used today. However, some companies feed multiple sites from remote operation centers. Feeding might be the most crucial operation considering economic viability for the farming company, and such centers intend to optimize the feeding practice. Compared to local control, more time, focus, and resources can be allocated to feeding and monitoring the salmon in the operation centers. At the farm, feeding is only one of several tasks farmers have in their daily operation. These tasks are briefly presented throughout this section.

Fish welfare monitoring

Section 2 has presented the general welfare needs of salmon and challenges in sea-based farming. In an operational context, the following paragraphs intend to describe how fish welfare can be monitored through operational welfare indicators (OWIs). The overall purpose of using indicators is that the farmers should be able to identify negative signs and make the necessary decisions and measures before it becomes a fish welfare issue. The OWIs presented are based on the handbook made by Noble et al. (2018), where an overview of the indicators is shown in Figure 25. These are the OWIs relevant to the farming of Atlantic salmon in sea cages.

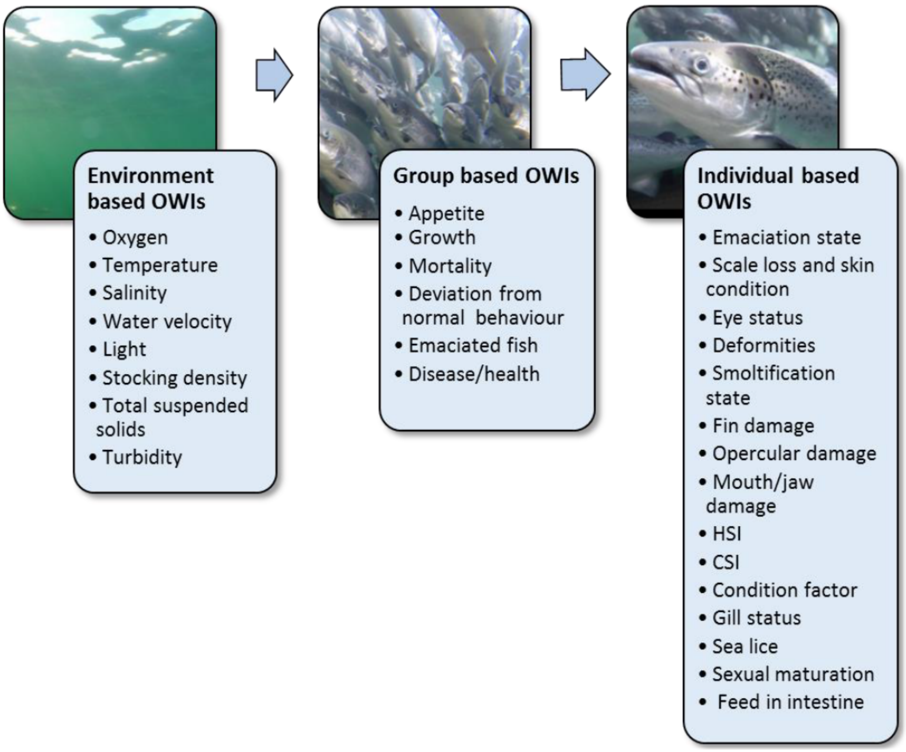


Figure 25: Operational welfare indicators for sea cages based on Noble et al. (2018)

In other words, these OWIs are hands-on tools that farmers should use at the facility as early warning signals and decision support for fish welfare. A workflow showing how OWIs should be applied together with LABWIs is shown in Appendix F. There are many OWIs related to sea-based farming, where some are more used and important than others. For instance, stocking density could be considered more a farming practice than a WI, and salinity has relatively little influence on fish welfare and growth compared to, e.g. oxygen, which is much more critical. Thus, only the OWIs considered most important for the daily operation are documented.

Environment based OWIs - Indirect indicators of fish welfare and looks at the environment surrounding the fish.

Temperature is one of the most critical parameters regarding the vertical distribution of the salmon, as the salmon swims to the depth with comfortable temperatures. The most preferred thermal range is not explicitly stated and varies throughout the life cycle. If temperature change occurs gradually and if the oxygen level is sufficient, the salmon generally adapt well to temperatures from 0°C to 23°C. However, low and high temperatures in this range are associated with suboptimal farming conditions. High seawater temperatures typically increase the risk of disease outbreaks, and low temperatures are associated with decreased growth rate and a longer healing time for wounds and illness. According to MOWI (2015), the optimal farming temperature range is 8-14°C. In the case of post-smolt, one should be aware of low temperatures(<6-7°C), as this increase the risk of winter ulcers.

Oxygen is another key OWI that provides valuable information about the fish's well-being. In situations with low oxygen saturation in the cage, the fish might experience hypoxia, leading to reduced appetite, stress, and even mortality. Special circumstances that can cause low oxygen levels and risk of hypoxia are further discussed in Section 4.4.2. The oxygen saturation inside the cage will depend on how much the fish consume and the water exchange rate, driven by the current. The salmon need more oxygen in the summer months as their metabolic activity increases with temperature. However, the concentration of dissolved oxygen is highest at low temperatures, i.e. the winter months, when the fish require less oxygen. In other words, the salmon's O_2 requirement and O_2 availability in water contradict each other during temperature/seasonal changes. Being aware of different situations and patterns that might result in low oxygen levels is important. In terms of values, 80% oxygen saturation is considered to be a conservative value for appetite/feed intake and healthy farming.

Group based OWIs is animal based indicators that address the population as a whole.

Appetite is a key OWI for the farmers. As mentioned previously, monitoring appetite is one of the primary tasks on the fish farm, and a lot of time is allocated to this operation in order to optimize feeding and growth. Suppressed appetite or changes to feed behavior might signal a possible welfare issue that, by proper monitoring, can be discovered at an early stage. However, experience and knowledge are key when using appetite as an OWI, as reduced appetite and pellet rejection might signal satiation or adverse environmental conditions, as previously discussed.

Mortality is probably the most applied OWI in sea-based farming and the only welfare indicator which is regularly reported to the Norwegian Directorate of Fisheries(once a month) (Stien et al., 2021). *Akvakulturforeskriften* (Ministry of Trade, Industry and Fisheries, 2021) requires that all Norwegian farms shall remove dead salmon from the sea cages on a daily basis. Based on all these available data, the Institute of Marine Research (IMR) has made mortality curves that farmers can use as a benchmarking tool throughout their production cycle. Such a curve is shown in Figure 26, with a plotted case made by Noble et al. (2018). The mortality curve is based on reported data from several thousand sea cages in the industry from 2009 to 2015, and provides a good picture of expected mortality in the first 15 months after sea transfer (Stien et al., 2016). Suppose mortality is registered higher than expected (green zone). In that case, it is a clear indication of an abnormal situation and that the farmers should start to investigate potential causes, especially if the trend continues. In this way, production decisions could be taken at early stages and avoid unnecessary suffering to the salmon, e.g. by euthanization. Insufficient smoltification of parts of the population is typically a cause of increased mortality during the first weeks after seawater transfer. The plotted example is an extreme case where the accumulated mortality is more than 40%. The average mortality after 15 months is approximately 13% (Stien et al., 2016).

Emaciated fish is a central OWI in the farmers' daily operation. These fish are dying and might experience low welfare for longer periods, as well as they might be a source for spreading diseases to the healthier population. As they are weaker, the fish usually avoid the central part of the cages where the feeding and the healthy fish are active. They generally have a poor appearance, thin, and some might have deformities. At the farm, the fish is referred to as "losers". An example is shown in Figure 27. Behaviourally, they typically occur at the surface, isolated from the school, and swimming slowly along with the net. The emaciated fish is not easy to observe on cameras. However, the OWI can easily be applied when the farmers have their daily inspections at the cages, where the "losers" are removed with a handheld scoop net. They occur most frequently during the early stages after seawater transfer, as typical causes for emaciated fish are failed smoltification and stress reactions due to the completely new environment in the sea cage. Other reasons might be diseases and sea lice. However, it is generally important to monitor the occurrence of emaciated fish, as increasing amounts of them can be an early warning signal of serious welfare issues.

Furthermore, emaciated fish is an example of **deviation from normal behaviour**. But changes to normal behaviour can also be less obvious and involve the whole school. Such changes are easier to detect through the underwater cameras, and the farmers must learn what is normal behaviour for their salmon at different sizes and seasons, as deviation might be signals of bad welfare and disease. Lastly, **disease/health status** of the population is periodically monitored by fish health personnel/veterinarians, as the fish can be subjected to several diseases throughout the seawater stages. It is outside the scope of this project to discuss these various diseases, but an overview of them is given in the handbook, section 3.1.5 (Noble et al., 2018).

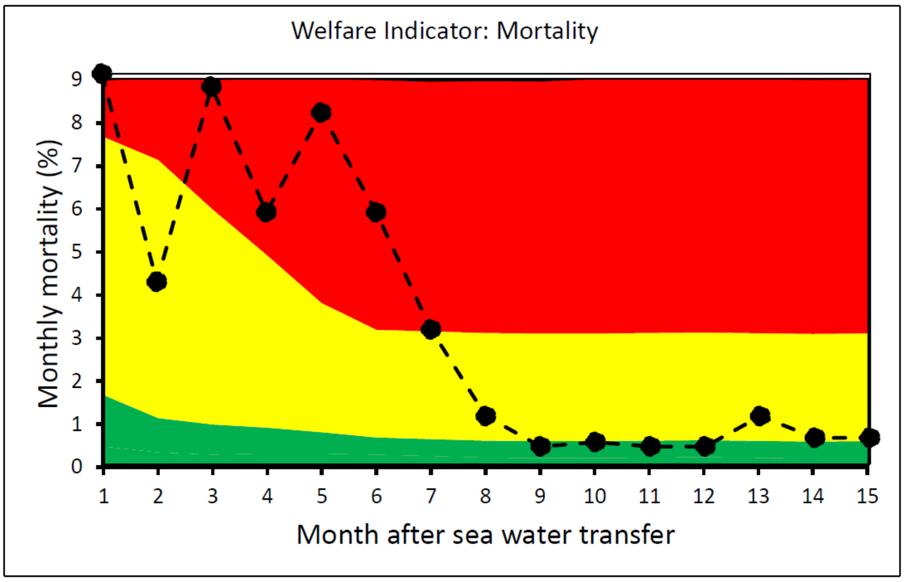


Figure 26: Mortailty curve (Noble et al., 2018)

(a) In the surface, swimming slowly near the net.

(b) Side-view

Figure 27: Emaciated fish (Noble et al., 2018)

Individual based OWIs are animal-based indicators to be applied during inspection and sampling of individual salmons.

Figure 25 shows an overview of all the different individual based OWIs which should be considered when sampling individual fish. Evaluation through these OWIs will give a clear indication of the individual's welfare. Some of the OWIs might provide a better understanding of the severity and prevalence of certain welfare problems, such as detecting the infectious disease AGD (Amoebic Gill Disease) through examination of gill status. The operation of lice counting (see next operation) is a good opportunity for the farmers to apply these individual based OWIs regularly.

Lice counting

The operation of counting lice is important to get an overview and control of the lice level at the fish farm. The Norwegian Ministry of Trade, Industry and Fisheries require counting with an interval of seven days when seawater temperature is greater or equal to 4°C, and every 14th day if below. Depending on region and season, a minimum of 20 or 10 salmons are sampled. The fish are typically captured by a scoop net attached to the vessel crane. Then, the fish are anesthetized, and for each salmon, lice are carefully counted and categorized by lice life stage. The sea lice level shall at all times be less than 0.5 adult female lice on average per fish at the fish farm. Exceeding this limit will require the fish farm to initiate delousing processes. The limit is lowered to 0.2 for a five-week period during the spring when the wild fish smolt migrates out of the rivers (Ministry of Trade, Industry and Fisheries, 2016b). The exact week numbers depend on regional belonging. Lastly, indications of sea lice levels can be obtained by studying the surface activity, as the jumping frequency increases with increasing lice infestation (Furevik et al., 1993).

Figure 28: Lice counting of an anesthetized adult salmon (IMR, 2011)

Daily inspection

Visual inspections of cages, barge, vessel, and other technical systems are performed daily. The technical and daily inspection of the sea cage is carried out to ensure that the cages are in proper condition and thus reduce the risk of structural failures. The daily inspections are performed according to official regulations (I. M. Holmen et al., 2018). This daily routine and dead fish removal (next operation) allow the farmers to be present at the cage and apply many of the animal-based OWIs on a regular basis. This brings consistency to the work of monitoring fish welfare.

Dead fish removal

As previously mentioned, the farmers must remove dead fish from the sea cages daily. Besides using mortality as an OWI, a daily collection of dead fish improves food safety and biosecurity, and also, by ensiling the dead fish, more of the fish gets utilized. The operation is performed with a collection system on board the working vessel, which the farmers attach to the vessel connector at the cage handrail. Then, as the farmer opens the air valve, pressurized air enters the cone and "lifts" the dead fish to the collection system by the vacuum created in the PVC hose. The collection system on board normally has a separation functionality to preserve alive cleaner fish. After collection, the dead fish is registered and brought to the ensilage system at the feed barge, where the dead fish is lifted onto the barge by crane. Although the regulation states that deviation from the requirement of the daily collection is allowed, uncollected dead fish for longer periods might have adverse effects on biosecurity and increase the likelihood of attracting predators. In other words, the risk to fish welfare and fish escape also increases.

Operating with cleaner fish - Feeding, monitoring and welfare

Cleaner fish, i.e. wrasses and lumpfish, is used as a continuous delousing method in Norwegian aquaculture. The cleaner fish eat the sea lice which have infested the salmon and is a gentle delousing method compared to other on-demand delousing treatments (see Section 4.4.2). Although the cleaner fish can help reduce the infestation density in the cage, they might not be efficient enough to keep the lice level underneath the limit of 0.2/0.5 adult female lice per fish, and expensive delousing treatments must be initiated. This can be due to varying efficiency among the cleaner fish and/or high lice density in the region. However, the cleaner fish have positive effects by delaying and reducing the amount the delousing treatments through the production cycle or even avoiding them under the right conditions. Therefore, over the past decade, the use of cleaner fish has increased rapidly, expanding from a total of 11 million in 2010 to 51.5 million in 2020, with a value of more than 1.26 billion NOK (Directorate of Fisheries, 2021a). Typically, 5-15 cleaner fish are used per 100 salmon individuals (SNL, 2022).

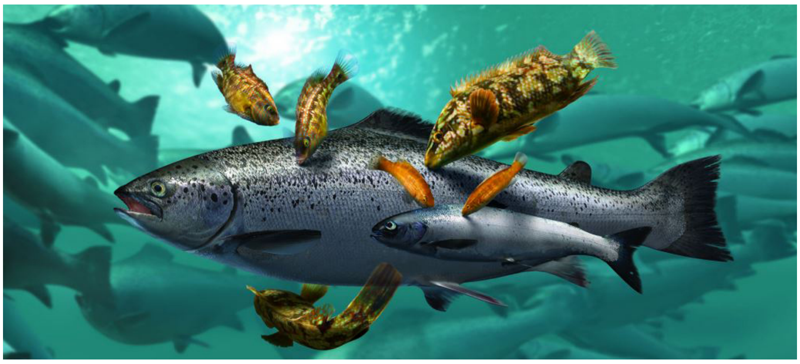


Figure 29: Wrasses grazing sea lice (Moen Marin, 2020)

However, operating with cleaner fish has its drawbacks. Wrasses and lumpfish are living organisms in the same way as the salmon and should be treated equally. Nofima, the same publisher as for the previously discussed welfare indicators, has also made OWIs for Ballen wrasse and lumpfish (Espmark et al., 2019). These will not be addressed, but an overview is shown in appendix H. *Akvakulturforeskriften* (Ministry of Trade, Industry and Fisheries, 2021) states that the same regulatory requirements apply for cleaner fish in terms of ensuring good fish welfare and sufficient feeding. The fish shall normally be fed daily, and the farmers must have good routines for feeding them. The sea lice as feed are not enough for the cleaner fish and must be fed with suitable pellets to maintain good nutrition and welfare. The fish also need the feed to be robust enough to seek and graze on sea lice (Espmark et al., 2019). Thus, as mentioned in Section 4.3, there are feeding stations for the cleaner fish, typically mounted on the handrail and close to the hide-outs.

The farmers need to place feed stations and hide-outs in a way that fulfils the cleaner fish's needs for feeding and shelter, as well as the positioning should allow for interaction between the cleaner fish and the salmon. Results from Nofima (Espmark et al., 2019) also show that the wrasses and lumpfish respond very differently to stress and have entirely different needs. Furthermore, removing the cleaner fish from the sea cage must be done in advance of operations which could harm the fish (e.g. delousing treatments). The latter is a requirement from *Akvakulturforeskriften* and intends to protect the cleaner fish from unnecessary suffering. Overall, optimizing the grazing efficiency through fish welfare monitoring, feeding, and handling equipment (feed stations, hide-outs) are resource-demanding for the fish farmers. If both species are used at the farm, the farmers must gain knowledge and understand the needs and behaviour of three species (including the salmon), making farming more complex. According to a national control campaign carried out by the Food Safety Authority, only 28% of the farms had a deviation from the regulations, and the farmers generally put a lot of effort into the cleaner fish's welfare (Norwegian Food Safety Authority, 2019). However, the campaign also revealed unacceptably high mortality of more than 40% (24 million in 2018), which raises ethical and sustainable questions about whether it is justifiable to continue this operation strategy in the future. The campaign states that the fish most likely cannot adapt to the sea cage environment or that their needs are not sufficiently met.

4.4.2 On-demand operations

Operations performed on-demand are delivery, delousing, net change, and net cleaning. These are sporadic operations that are needed based on the condition of the salmon or the net bag. If disregarding the net cleaning operation, these operations usually involve several vessels and people and frequent use of cranes and winches. Specialized and heavily equipped service vessels, well-boats, and/or barges are chartered by the fish farm to conduct and assist throughout the operations. This is crucial to perform the operation as safely and efficiently as possible. Figure 30 shows an operation involving several vessels, gathered to crowd the salmon in order to either treat or deliver the fish. This section is mainly based on descriptions from the project thesis (Nesje, 2021).

Figure 30: Complex operation (Directorate of Fisheries, n.d.)

Delivery

When the salmon reach harvestable size (approximately 4-5kg (MOWI, 2015)), large well-boats or live fish carriers are hired to transport the salmon from the fish farm to the processing plant. The well-boat is moored to the cage and nearby buoys, and pumps the fish into large tanks where the fish and water quality are monitored through cameras and sensors (AS, n.d.). The fish needs to be gathered to get all fish pumped on board and ensure an efficient process. The gathering is usually done by emptying the cage of equipment (hideouts, spreader, dead fish equipment, cameras, sensors, etc.), and afterwards installing a seine net (Norwegian term: *orkastnot*) on the inside of the net bag. When the fish are enclosed by the seine net, a "pearl-line" with great buoyancy capability is placed underneath the seine and slowly pulled towards the well-boat, gathering the fish around the suction pipe inlet. Figure 30 illustrates the process. The balance between pulling speed and pumping is crucial and requires continuous monitoring of the school and good communication between well-boat and fish farmers. If not done properly, the fish will get too crowded, a central welfare issue.

Crowding restricts the salmon's free swimming and behavior control. Furthermore, the fish are exposed to a lot of physical contact with other individuals or rearing units, which may lead to scale loss and/or wounds, especially in low-level temperatures. Lastly, oxygen levels during crowding may fall as oxygen consumption increases with increased activity. The problem amplifies with reduced water exchange during low current speeds. The condition of hypoxia may occur as a result of increased activity and reduced availability of dissolved oxygen. The salmon experience hypoxia as stressful, as well as it negatively affects aerobic metabolism, causing a reduction in activity, appetite, and growth (Hvas and Oppedal, 2019). All these crowding outcomes are stressful for the fish and may lead to reduced meat quality. The high-stress levels and muscle activity decrease the rigor mortis time and cause problems in the process plant, as well as it could lead to texture softness and gaping in the fillet (Noble et al., 2018). If crowding and high stress are present for longer periods, the stress may trigger several metabolic changes, resulting in reduced growth, immunosuppression, and an increase in mortality (Delfosse et al., 2016). Overall, it is of great importance to monitor crowding related operations closely and assess/adjust the operation based on OWIs. Noble et al. (2018) have created customized OWIs for the crowding operation, shown in Appendix I. The pumping and other direct handling activities are also experienced as stressful for the salmon.

Delousing

There are several approaches to lice control and methods for performing delousing. Methods can be distinguished by the ones that use chemotherapeutants and non-medical treatments. Furthermore, the industry has four dominating chemotherapeutants and two main non-medical principles. The most used chemotherapeutants are azamethiphos, cypermethrin, deltamethrin, and hydrogen peroxide (Overton et al., 2019). Meanwhile, non-medical principles are mechanical and thermal treatments. Example of mechanical and thermal delousing are the Hydrolicer® and the Thermolicer® or the Optilicer®, respectively. However, the industry has, in recent years, experienced a rapid change from chemotherapeutants to non-medical methods (Overton et al., 2019). Freshwater treatments are also a non-medical method that has been recently practiced and showed promising results. But, there are some concerns regarding the ability of sea lice to develop freshwater resistance (Ljungfeldt et al., 2017). Regardless of the method, these operations require a lot of vessels and people, and bring significant risk to both human and fish welfare if not controlled properly. Delousing as bath treatment with tarpaulin and hydrogen peroxide is illustrated in Figure 31. The chemicals used during delousing may create wounds and discomfort for the salmon, however, it is not considered as critical in terms of food safety (S. Holen et al., 2018). In the case of mechanical or thermal treatments, the fish needs to be crowded and pumped into a treatment system, typical a well-boat or delousing barge. Thus, in terms of crowding, mechanical and thermal delousing involve the same risks as described above. The risk related to crowding is to some degree mitigated by fasting the fish up to four weeks before the crowding operation, as this will lower the fish's oxygen demand and empty the gut of the fish. As a result, the salmon will be more resistant to acute stress, as well as poor water quality due to feces will be avoided (IMR, 2020). On the other hand, fastening results in loss of growth and might prolong the production cycle.

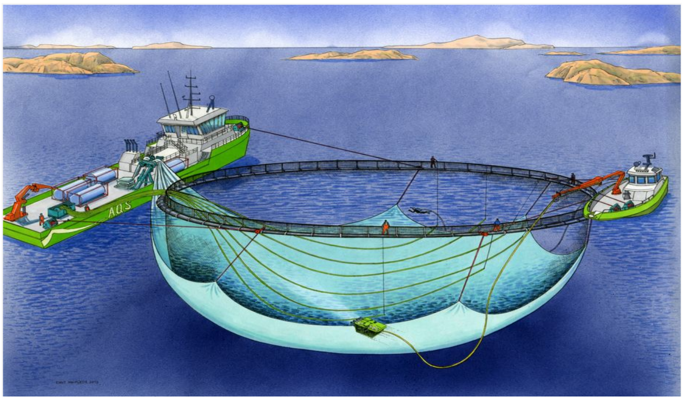


Figure 31: Bath treatment using tarpaulin (AQS, n.d.)

Marine biofouling poses a significant problem for the Norwegian aquaculture industry. The nutrient-rich water around the cages attracts macro and micro foulers, consequently causing gradual occlusion of net openings and thus increasing the solidity ratio. This results in increased weight and drag of the cage structures, and thereby, in case of strong currents, deforming the net bag and thus reducing available volume for the salmon. The fouling is not equally concentrated down the net wall, and it is proven that levels of fouling decrease with depth (Dürr and Watson, 2009).

Net cleaning

In Norwegian aquaculture, the issue of fouled nets is typically handled by combining the use of copper-based coatings on nets and regularly underwater net cleaning (Bannister et al., 2019). Net cleaning is usually performed by hired and specialized service vessels, which are equipped with ROVs for cleaning and inspections. This operation is not as complex and work-demanding as those previously described. The cleaning can be performed without involvement by the fish farmers and does not interrupt the feeding or other operational aspects at the farm. However, the salmon are exposed to stress and biofouling debris, which might decrease water quality and compromise gill health in case of frequent cleaning. Biofouling intensifies during summer/fall, and in some cases, especially during the peak of the biofouling season, farms need to clean their nets every second week (Uglem et al., 2020).

Net change

An alternative strategy to copper-impregnated nets and cleaning, is to use nets without coating and perform regular net changes. The fouled net is then cleaned in net washers on shore. A net change is a complex and hazardous operation that requires several service vessels to assist the process. The net change is usually performed while the salmon are in the cage, introducing risk to the environment in terms of escaping. Additionally, considering occupational safety, cranes and winches are frequently used during the replacement. Replacing the net could either be done by sewing the nets together or by surrounding the old net with the new one (Egersund Net, 2020). The surrounding method has similarities with Figure 31 and requires the different vessels to pull/winch ropes simultaneously and at the same speed. Net change is, therefore, a complex operation requiring continuous collaboration between vessels and with a significant risk to both people and the environment if not appropriately controlled. Another motivation for net change is to increase the mesh size.

5 The new system - Midgard Subsea system

This section describes the Midgard Subsea sea cage concept developed by ScaleAQ. An application for a development permit was rejected back in 2017 (Directorate of Fisheries, 2021d). Since then, ScaleAQ has been working with the concept, where an early illustration is shown in Figure 32. The figure is still representative and shows the floating collar system, the net bag and the expansion system. Besides these components, the system is to a large degree conceptual, especially in terms of the auxiliary equipment.

In simple terms, the Midgard subsea system is a conventional sea cage with one planned modification: To submerge the net bag. The motivation is, as previously introduced, to reduce sea lice pressure, as well as to be able to operate in more exposed locations. Compared to the basic system, the floating collar system and the net bag structure are, to a large extent, similar constructions and have the same circumference (157m). Many planned modifications to the system are a consequence of submergence, but some components and operations have changed independently of the descended net bag. The purpose and functionality of the components are mainly the same. Thus, the identification of differences primarily addresses physical design changes, as well as operational changes.

This step of the analysis aims to compare the two systems and identify the difference between them. Section 5.2 shows the result of the comparing process, where each identified difference is enumerated and described. In total, 40 differences were identified. Components and operations not mentioned in the list must be considered unchanged, i.e., similar to a conventional sea cage. As mentioned in the methodology chapter (Section 3), components and aspects with no planned modifications do not need to be described again.

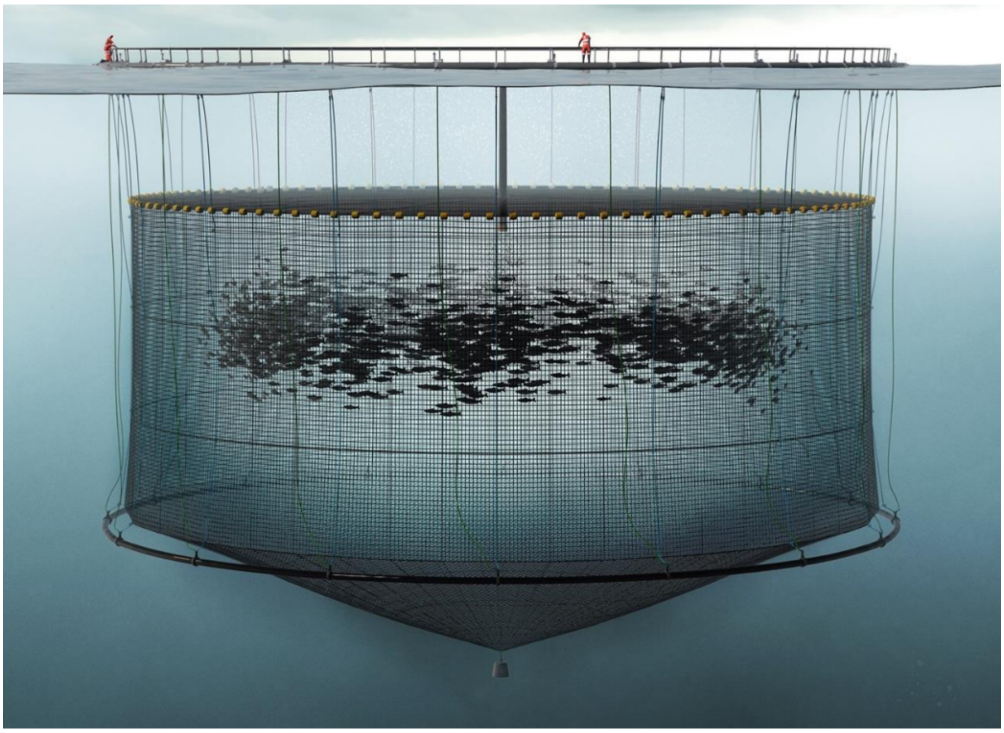


Figure 32: Midgard SubSea cage. (ScaleAQ, 2017)

5.1 Information basis

The author was granted access to the internal visualization software *Scaleworld*, which is a 3D platform that gathers and illustrates all ScaleAQ's products and models in an artificial fish farm environment. The technical model and design intentions of the Midgard Subsea cage are considered confidential information by ScaleAQ, and therefore are technical illustrations excluded from the main part of the thesis. The illustrations are attached to the separate Appendix J, only available for the author, ScaleAQ, supervisors, and censoring purposes.

Due to an early design phase, the 3D model of the subsea cage was limited in terms of auxiliary equipment. The auxiliary equipment available in the model was the expansion system and the mortality system, as shown in Appendix J. The changed expansion system is an older and finalized modification that ScaleAQ has integrated into traditional sea cages and is a part of their current product portfolio. Apart from these two systems, the net bag was empty of auxiliary equipment in the 3D visualizer. Technical information on the design intentions of missing auxiliary equipment was provided through digital meetings. The same meetings also provided the author with information on operational intentions and modifications. Overall, the descriptions are based on provided information through the 3D platform and digital meetings.

5.2 List of differences

Table 8: System boundary differences

Category	No.	Title	Description
Technical interface	1	External interface change	The air pipe (EI2) now enters the system boundary in a submerged state. The power cables (EI4) and the feeding pipe (EI3) still float and enter the system boundary in the water surface.
Operating condition	2	More remote	The cage allows for production further from shore (but not offshore), i.e. the distance to local services and communities is longer.
	3	Environmental condition.	Changed environmental entities. Located in more exposed areas means stronger winds and larger waves. $H_{s,50\text{year}}$=6-9m is the new wave exposure. In terms of current, the net bag and fish will experience more even current conditions as the effect of fluctuating wind-generated current is eliminated, and tidal currents will most likely be reduced further from shore.
External threats	4	Shipping traffic	Increased traffic of large vessels (cargo, tankers, offshore fishing fleet, OSV, etc.) and less traffic of smaller vessels (20-30 feet open fishing vessels, tourists ferries, passenger high-speed craft etc.)
	5	Storms	Higher frequency of storms and extreme weather.
	6	Submarines	Potential higher frequency of submarines
	7	Whales and blue fin tuna	Potential higher frequency of whales and blue fin tuna
	8	Predators	Potential lower frequency of otter and mink.
Support functions	9	Diving and cleaner fish delivery	Due to the submerged condition, diving will be inappropriate. As the main operational state is submerged and elevation is undesirable, diving actions will be reduced and tried to be replaced with ROVs. Cleaner fish delivery is no longer applicable.

Table 9: Technical differences

No.	Title	Change mode			Description	Basic tag no.
		New	Rem-oved	Other m.		
10	Floaters	**X**			**Net bag change.** Floaters are attached to the top of the net (top-rope) to lift and hold the shape of the net bag while elevating the bottom ring. They are sewed to the top rope independent of each other.	n/a
11	Ceiling	**X**			**Net bag change.** A net ceiling is sewed to the top rope to prevent fish from escaping. The ceiling has the same mesh size as the rest of the net bag. In order to remove the net ceiling, the current idea is to have a zip-functionality.	n/a
12	Extended side-ropes			**X**	**Net bag change.** The entire net bag and connected auxiliary equipment are suspended to the floating collar by extended side ropes. The ropes are extended by 30 meters. Only the side ropes linked to the cross-ropes (i.e. lifting-ropes) are extended. The amount of these ropes is still 20. In practice, the extension is not done by extending the side rope itself, but a separate fiber-sling is connected to a fastening loop at the end of the side rope. But for simplicity, the term "extended side ropes" is used. The top of the rope is made out of chains.	2.5
13	Winch	**X**			**Floating collar system change:** The winch elevates or lowers the bottom weight ring when needed. Lifting the bottom weight ring is previously done by single-point lifting using a crane from a service vessel. Now, the ring is elevated/lowered with remotely operated winches that simultaneously lift all suspension lines.	n/a
14	Air dome	**X**			**Auxiliary equipment change:** The air dome is introduced to the system to give the salmon access to air. The product design is unknown. However, the dome will be placed high and centered in the net bag, but with no physical connection to the net ceiling. Fastenings shall be to load-bearing elements in the net bag (top or main rope).	n/a

Table 9: Technical differences

No.	Title	Change mode: New	Change mode: Removed	Change mode: Other m.	Description	Basic tag no.
15	Feeding system			**X**	**Auxiliary equipment change:** The polyethylene feeding pipe enters the cage through the ceiling above the air dome and releases feed at a specific distance from the center, where the feeding does not interfere with the air dome. The product design is unknown, but it will most likely be several feeding points or a ring, spreading the feed at a given radius. The feed is also transported with water, not with air as for the basic system. Lastly, the feeding pipe is attached to the floating collar before going down and through the net ceiling.	3.3
16	Camera system			**X**	**Auxiliary equipment change:** The camera system will now be stationary with fixed cameras mounted in the lower part of the net bag, pointing upwards.	3.2
17	Mortality system			**X**	**Auxiliary equipment change:** The mortality system will still use air through a PVC hose to transport/lift the dead fish out of the bottom of the cage. However, the transport hose will go underneath the net bag and up somewhere outside the system boundary. In other words, there will be no mortality equipment inside the net bag or on the floating collar system, and the operation will take place somewhere outside the system boundary. The design has some uncertainties, but appendix J shows the concept.	3.4
18	Cleaner fish components		**X**		**Auxiliary equipment change:** Hideouts and feeding stations for cleaner fish are no longer a part of the system.	3.6

Table 9: Technical differences

No.	Title	Change mode			Description	Basic tag no.
		New	Rem-oved	Other m.		
19	Bird protection system		X		**Auxiliary equipment change:** The bird net is removed as there is no need to protect from flying predators at surface level. However, the plastic clamps and GRFP rods will still be assembled to the rail support. The intention is that they shall function as "ceiling-lifters" when the net bag is in the upper position. In this way, the rods can lift the net ceiling and enable air access for the fish along the floating collar, or they can be used as a tool for raising the net when the ceiling is to be disassembled.	3.8
20	Sea lice camera	X			**Auxiliary equipment change:** The system will be installed with a sea lice camera that enables automatic and continuous counting of lice. The Norwegian Food Safety Authority assess such equipment and potentially gives exemptions from manual lice counting (Norwegian Food Safety Authority, 2020). Aquabyte is an example of a company that has received a permit to use their sea lice camera.	n/a
21	Interface, fastening of aux. eq.			X	**Internal interface change:** The fastening of auxiliary equipment inside the net bag (i.e. sensor system 3.7, light system 3.9, camera system 3.2, feed system 3.3, air dome and sea lice camera) will be fastened to the load-bearing elements (top rope or main rope) in the net bag with ropes. Such equipment is attached to the handrail or rail support in the basic system.	II.5, II.10, II.13, II.14
22	Interface, collars-netting		X		**Internal interface change:** The submerged state of the net bag removes the possibility of physical interaction between the floating collar and the net.	II.1
23	Interface, expansion system - collar system.			X	**Internal interface change:** The bottom ring suspension line is now slack and connected to the new winch. It is also made out of ropes/fiber-material instead of steel chains..	II.4

Table 9: Technical differences

No.	Title	Change mode			Description	Basic tag no.
		New	Rem-oved	Other m.		
24	Interface, expansion system - net bag.			**X**	**Internal interface change:** The entire bottom ring and its weight are suspended in the side ropes (lifting ropes). The suspension line is, as mentioned, slack. In the basic system, the expansion system was suspended to the collar system through the suspension line and only took up the horizontal movement of the net bag. In contrast, now, the whole weight of the ring is carried by the side ropes in the net bag, which further transfers the load to the floating collar system through the extended side ropes.	II.15
25	Interface, handrail		**X**		**Internal interface change:** Various interfaces towards the handrail (1.4) are removed. This comprises several auxiliary equipments as well as the ropes used to attach the top rope to the handrail (creating the jumping net).	II.3, II.9, II.10, II.11, II.12, II.13, II.14.
26	Interface, fastening net bag- collar system.			**X**	**Internal interface change:** The fastening between the floating collar system and the net bag has fewer attachment points. In the basic system, the main rope in the net bag was attached to every steel bracket/rail support (i.e. attachment point for every side rope), whereas now it is only the extended side ropes that are attached to the steel bracket. In other words, the number of attachment points between the floating collar system and the net bag is reduced from 60 to 20. Furthermore, these attachment points are moved on the steel bracket, from above the inner collar to between the collars. The extended side ropes are fastened to the collar by a steel splint. The interface is shown in Section J.	II.3

Table 9: Technical differences

No.	Title	Change mode New	Change mode Rem-oved	Change mode Other m.	Description	Basic tag no.
27	Interface, submerged net-entries			X	**Internal interface change:** The feeding pipe, power cable, and the air supply to the air dome need to enter and penetrate the netting. Thus, there will be more entries in the net compared to the basic design, where the only entrance was for the feed pipe (II.16). However, the intention is to have only two entries, where the feeding pipe goes through the ceiling, and the rest (air supply and power cables) enter the bottom of the net bag, alongside the mortality system. The design of entries is not decided. Another important difference in this context is that the entries are submerged.	II.16

Table 10: Operational differences

No.	Title	Change mode New	Change mode Rem-oved	Change mode Other m.	Description
28	**Normal operation:** Submerged as main state	X			The main operational state of the cage structure is submerged. The top of the net bag is to be submerged to 20-30m under the water surface. This shall be the operational state throughout the whole production cycle, from seawater transfer to delivery of fully grown salmon. The net bag will only be elevated in case of emergency or on-demand operations (delivery, delousing, net-wash, and repair/maintenance). The reason for this is the concern of sea lice and their adaptability to remain and spread in the population after submergence. Thus, the fish will only be monitored through the stationary underwater cameras during normal operation.
29	**Normal operation:** Start-feeding		X		The operation of hand-feeding smolt is not to be carried out. The net bag is to be submerged shortly after seawater transfer. This is due to the increased risk of lice infestations and harsh environmental conditions for fish and personnel.
30	**Normal operation:** Feeding			X	The operation of feeding from barge or operation centers are mostly the same. However, the new camera system of stationary cameras in the cage might be less flexible than the conventional camera system, where the farmer can monitor and follow the feed activity along two axes (surge and heave).

Table 10: Operational differences

No.	Title	Change mode: New	Change mode: Removed	Change mode: Other m.	Description
31	**Normal operation:** Sea lice monitoring			**X**	The operation of counting sea lice manually is replaced with continuous monitoring through a sea lice camera. Additionally, the farmers have lost their opportunity to get an indication of sea lice prevalence in the population based on surface activity.
32	**Normal operation:** Fish welfare monitoring - OWI usage			**X**	Environmental OWIs are applied the same way through sensors. The animal based OWIs (group and individual) have reduced operability: The group-based OWIs of appetite and mortality are still valid, as monitoring feeding is done through cameras and collecting dead fish is still possible. Thus, the OWIs that are influenced are the ones the farmers usually apply when they are present at the sea cage. The proximity to the fish which the farmers have in conventional sea cages is now gone. The fixed underwater cameras can monitor the welfare of the population as a whole, but the occurrence of emaciated fish is now challenging to monitor. Emaciated fish (loser fish) is a central OWI and is particularly important in the early stages after seawater transfer. Further, the deviation from normal behaviour (group-based OWI) could be more difficult to monitor if the stationary camera lenses are dirty or in the case of turbid water. Proximity to the fish has also been important to detect individuals who are suffering, e.g. fish that is blind or has deformities. Furthermore, other individual OWIs such as fin damage, skin condition, shortened/damaged operculum, sexual maturation, jaw damage and gill status are now difficult to use. In a conventional sea cage, these OWIs are applied regularly through manual lice counting. Furthermore, for the basic system, several of the animal based OWIs are also being used consistently during the daily operation of *daily inspection.*

Table 10: Operational differences

No.	Title	Change mode: New	Change mode: Removed	Change mode: Other m.	Description
33	**Normal operation:** Fish welfare monitoring - New OWIs	**X**			The salmon have an open swimming bladder and need access to air to refill their swimming bladder and maintain buoyancy control. Noble et al. (2018) have proposed three OWIs for depleted swimming bladders that should be used in submerged cages. These group based OWIs are as follows: • Abnormal tilt-angles A "tail-down head-up" swimming position is a typical indication of an empty swimming bladder. Tilted swimming is most frequent at night, and long-term experience of this position might lead to deformities due to increased loads in the tail region muscles. • Surface activity After raising the net bag to the surface, the farmers should pay extra addition to the surface activity. If the fish exhibit high activity after being brought back to the surface, this usually means that they have not utilised the air dome to fill their swimming bladder. • Increased swimming speed An empty swimming bladder means loss of buoyancy, and the fish will start sinking. This is often compensated for with increased swimming speed. Additionally, the group based OWIs of appetite and growth should gain even more attention. Reduced growth and loss of appetite might indicate poor utilization of the air dome and that the fish are experiencing long periods of no air access/"submerged condition".
34	**Normal operation:** Cleaner fish		**X**		Operating with cleaner fish is no longer applicable.
35	**Normal operation:** Daily inspection			**X**	Visual inspection of the upper part of the netting/net bag is no longer possible. The floating collar and related technical equipment must still be inspected.

Table 10: Operational differences

No.	Title	Change mode: New	Change mode: Removed	Change mode: Other m.	Description
36	**Normal operation:** Dead fish removal		**X**		The daily operation of removing dead fish by a working vessel fastened to the cage and local control of the mortality system is no longer applicable. With the new mortality system previously described, the operation and collection of dead fish shall take place somewhere outside the system boundary.
37	**On-demand operation:** Net-change		**X**		The net-change operation is no longer applicable due to more auxiliary equipment interfering with the net bag, making the process more complex and time-demanding. It will be more convenient to use a net bag that has the properties of lasting the entire production cycle and with an optimal solidity ratio.
38	**On-demand operation:** Delousing			**X**	The amount and need for delousing treatments will most likely be reduced. As aforementioned, the operation is in principle the same.
39	**On-demand operation:** Net cleaning			**X**	In the submerged state, the net bag avoids the upper water column where the conditions for growing biofouling are better. Thus, the amount and need for net cleaning will most likely be reduced. As aforementioned, the operation is in principle the same.

Table 10: Operational differences

No.	Title	Change mode			Description
		New	Rem-oved	Other m.	
40	**On-demand operation:** Lift/lower the net bag	**X**			As previously mentioned, the main operational state is submerged, and lifting/lowering of the net bag is only to be carried out in case of emergency, freshwater transfer, delivery, delousing, net wash, repair or required maintenance. The operation is completely new, and there are still details regarding the execution which are uncertain and under development. Thus, the following simple steps describe the current status and procedure of elevation based on the provided information. 1. Activate winches and elevate the bottom weight ring by the wireless remote controller. 2. As extended side ropes get slack, pull these in by hand. 3. Fasten the net bag's main rope to the floating collar steel bracket the same way as for the basic system. 4. Using the bird net rods (3.8.3), lift the ceiling and fasten the top rope to the handrail (same fastening as the basic system). 5. If needed, unzip the ceiling and remove it by a working vessel crane. Then, remove auxiliary equipment inside the net bag and execute the required on-demand operation, e.g. delivery. For submerging the net bag, reverse the procedure.

6 Result

This section presents the result of the change analysis applied to the Midgard Subsea system. The section starts by establishing a risk assessment framework before presenting the analysis according to the methodology description. System descriptions (step 1.4) and step 2 (List of differences) are excluded from the section and documented in Section 4 and Section 5.

6.1 Risk assessment framework

6.1.1 Purpose and delimitation

The conventional sea cage and its associated risk picture are well-known in the industry. The Midgard subsea cage is, as mentioned, more or less a revision of a conventional sea cage, where the primary difference is a submerged net bag. In this regard, the purpose of this risk assessment is to gain more knowledge on how the intended changes will influence the current risk picture. The conventional sea cage is associated with several central and well-known hazardous events, such as fish escape, sea lice/disease spread, increased mortality etc., and there is a need to understand if the intended modifications will have a positive or negative effect on these events, or even influenced them at all. The subsea cage is at a conceptual stage, and there is also a need to see if the changes have introduced new hazards/events. Answers on how, and to what degree, the intended changes will impact the risk will give decision support to whether the modifications can be preserved or if other decisions must be taken. Other decisions might, for instance, be to implement the proposed risk reduction measures, re-design the intended modification, do a more detailed analysis of highlighted issues, or accept the risk by the ALARP principle. These decisions are to be taken by ScaleAQ. In addition to highlighting the risk impact of every single key difference, the change in the overall risk of every selected hazardous event will be discussed and determined.

The work is at a preliminary level and does not quantify risk in detail, and most of the assessments will be based on expert judgments. The author has one year of experience as a fish farmer and is therefore familiar with the technical and operational aspects of conventional fish farming. On the other hand, besides the already presented material in terms of fish welfare/growth, the author's knowledge basis is limited when it comes to biology and the various factors that might influence fish welfare. Furthermore, the justifications of risk levels are to be supported with scientific research and statistics if available. The intention is to enhance the reliability of results and thus reduce uncertainty in case of limited knowledge, particularly related to the biological aspects. Lastly, justification and evaluation of risk should be based on critical thinking and conservative assessments.

Other limitations and assumptions:

- Although the system boundary is defined around the cage system, assessment of frequency and severity should, in some cases, consider the whole fish farm. A fish farm typically consists of six to 12 identical sea cages, and the likelihood for certain events to occur will depend on the operational configuration of the farm. For instance, if the farm had only one cage, there would probably be fewer fish escapes and welfare issues (per cage) due to more resources/cage. If operating a single cage requires three employees, managing a farm with 12 cages will not have a corresponding 36 farmers. In other words, this nonlinear relationship between farmers and cages makes it necessary to consider the farm as a whole when assessing the risk associated with the operational aspect of the cage. Thus, the assessment will be based on a fish farm equipped with eight Midgard subsea cages.
- It is assumed that if the subsea cage is elevated and fish get infected by lice in the upper water layers, the sea lice will endure and spread after descending. This assumption is based on the concern about the sea lice's ability to adapt and remain in depth-based farming (Coates et al., 2020).
- The assessment will be based on a remote site location that has no shelter from rocks and islets, i.e. open waters along the coast. As defined in Section 5, the location is not offshore and wave height is $H_{s,50\text{year}}$=6-9m

6.1.2 Values to be protected

The values to be protected in the risk assessment corresponds to the risk dimensions presented in Section 2. However, the dimension of *food safety* was not found relevant for the purpose of this analysis and therefore excluded. The other dimensions are included and shown in the value hierarchy, highlighted with an orange color. Since the risk dimensions function as principal values in fish farming, a secondary level of values was made for this analysis and denoted by a blue color in the hierarchy. Safeguarding the principal values depends on the lower level values and is to a large degree protected by measures intended for these underlying values.

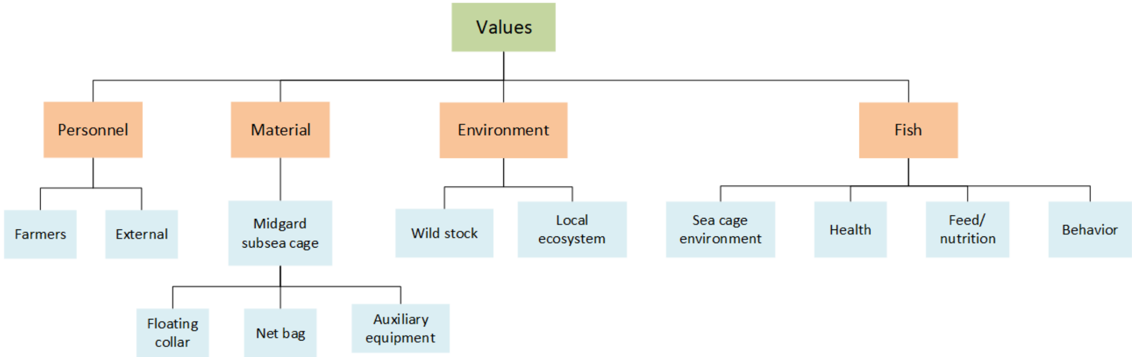


Figure 33: Value hierarchy

Personnel. The personnel to be protected are all relevant personnel present at the cage throughout the production cycle. This includes the farmers operating the fish farm and external personnel involved in the various on-demand operations. Short-term cage visits from external people such as sub-suppliers performing maintenance/repair, veterinarians, school visits, representatives from authorities, companies or similar are not considered in the assessment.

Material. The material values that are considered are the Midgard subsea cage and all related equipment within the system boundary, as described in Section 5.

Environment. The wild Atlantic salmon population is a central value regarding environmental protection in fish farming. The wild stock must be protected from farmed fish in terms of both physical interaction and infectious diseases/parasites sourced from a sea cage. The local aquatic environment is also a central value that should not be negatively impacted by the sea cage in terms of waste and pollution, both in the benthic zone and at the water surface.

Fish. Protecting the fish is all about ensuring a good welfare status. Thus, the secondary level of values reflects the needs of the salmon, as fulfilling these will protect the fish from hunger, discomfort, injury, disease, distress and panic. In other words, fish as a value is safeguarded as long as the fish thrive. The welfare needs are shown in the hierarchy, as well as previously presented in Section 2.

6.1.3 Risk acceptance criteria

The change analysis has an overall aim to assess change in risk based on risk contribution for a set of key differences between the two systems. In order to evaluate if the change in risk is acceptable or not, some predefined acceptance criteria need to be established. It is important to mention that establishing criteria and decisions on acceptance is to be done by ScaleAQ and that the following criteria are just a suggestion. A part of the suggested criteria is to apply the principle of ALARP in the evaluation process. ALARP is presented in Section 2. Then, the proposal is that risk is only accepted if the risk impact of the key difference, i.e. $\text{RPN}_{i,d}$, is below the ALARP region. The proposed ALARP region is shown in Figure 34. In the analysis, risk reduction measures are proposed for every key difference that contributes with an ALARP risk level or higher, and thereby providing ScaleAQ with possible measures that could be evaluated against cost and potentially implemented, depending on decisions.

Risk accepted if:

$$RPN_{i,d} < ALARP$$

Figure 34: ALARP region

6.2 Classifications

6.2.1 Likelihood

A suggestion of likelihood classification by Rausand and Haugen (2020) was found suitable for this analysis and presented in Table 11. However, the lowest level is customized for the change analysis. The level will be assigned to a key difference that, by its effect, will remove the hazard or somehow make it impossible for certain events to occur. An eliminated hazard or harmful event is a positive change in risk and must be included. But, an event that cannot occur has no consequences either, and normal practice of measuring risk becomes unsuitable. Thus, in the case of eliminated events, the addition of likelihood and severity will no longer apply, and the corresponding $\text{RPN}_{i,d}$ will be assigned with the value zero.

Table 11: Frequency classes adapted from Rausand and Haugen (2020).

Freq. class, L*i*		**Frequency [year^{-1}]**	**Description**
5	Frequent	10-1	Event that is expected to occur frequently
4	Occasional	1-0.1	Event that happens now and then and will normally be experienced.
3	Possible	10^{-1}-10^{-2}	Rare event that will possibly be experienced
2	Remote	10^{-2}-10^{-3}	Very rare event that will not necessarily be experienced in the system
1	Improbable	10^{-3}- 10^{-4}	Extremely rare event
0	Elimination	0	Eliminated event by the intended change.

6.2.2 Consequence

Table 12 shows the consequence classification. The selection of consequence categories is guided by the abovementioned values. Each class is defined based on the degree of severity if a harmful event occurs. Some categories are quite generic and apply to the first level in the value hierarchy, whereas others are customized for secondary level values. Nevertheless, the classification is found to be sufficient for assessing the consequence of most of the hazardous events that could occur in a sea cage. Apart from *fish growth*, all the categories are sourced from literature and linked with references. The category of *fish growth* is made by the author and further validated by Ole Folkedal, a researcher at IMR.

Table 12: Generic and customized consequence classification, adapted from different sources.

Consequence types	Consequence class, S*i* Catastrophic 5	Severe loss 4	Major damage 3	Damage 2	Minor damage 1
People (Rausand and Haugen, 2020)	> 1 fatality	1 fatality	Permanent disability, prolonged hospital treatment	Medical treatment and lost-time injury	Minor injury, annoyance, disturbance
Material (Rausand and Haugen, 2020)	Total loss of system and major damage outside system area	Loss of main part of system; production interrupted for months	Considerable system damage; production interrupted for weeks	Minor system damage; minor production influence	Minor property damage
Environment (Rausand and Haugen, 2020)	Time for restitution of ecological resources ≥5 years	Time for restitution of ecological resources = 2–5 years	Time for restitution of ecological resources ≤ 2 years	Local environmental damage of short duration (≤ 1 month)	Minor environmental damage
Fish escape x=escaped fish (Standard Norge, 2021)	x > 500 000	150 000 < x ≤ 500 000	10 000 < x ≤ 150 000	100 < x ≤ 10 000	x ≤ 100
Fish welfare (SalMar, 2021)	Extreme/acute mass death or welfare incidents/disease that cause serious suffering.	Prolonged exposure / irreversible stress or physical damage. Prolonged high mortality or suffering.	Lasting exposure, notifiable disease, or recurring impacts. Example: aberrant mortality (0.75% per week, > 0.5 kg)	Longer moderate exposure, disease, or stress. Example: increased mortality (0.2% per week, > 0.5 kg)	Short term exposure, stress, reversible
Fish growth (Ole Folkedal, personal communication)	Extreme deviation in growth rates to most of the population. RGI ≤ 40%. I.e fish growth is at least 60% worse than expected.	Significant deviation in growth rates to most of the population. 40% < RGI ≤ 60%	Large deviation in growth rates to the majority of the population. 60% < RGI ≤ 80%	Some deviation in growth rates to parts of the population. 80%<RGI≤95% Or a small group with significant growth deviation	Minor deviation in growth. RGI > 95%. Or few individuals with extreme growth deviation (e.g loser fish).

6.3 Hazardous events and current risk levels

The hazardous events that were found important and relevant for the purpose of this analysis are shown in Table 13. The events are selected from various standards and literature, shown in the fourth column. Further, the events are sorted according to the principal values, shown in the first column. Each hazardous event i can potentially cause harm to the value, and the associated risk level in conventional fish farming is shown as $\mathrm{RPN}_{i,B}$, where B denotes the basic system.

The selected hazardous events are well-known in the industry, and the current risk levels for conventional sea cages are thoroughly assessed and documented. Thus, for the purpose and effectiveness of this change analysis, where several hazardous events are to be evaluated, the current risk levels are based on available literature and discussions. Mainly, the risk levels are determined by the most recent risk assessment published by the Institute of Marine Research - *Risk assessment in Norwegian Aquaculture industry 2021.* Hazardous events not covered in the IMR report are settled based on a meeting and discussions with PhD student Ingunn Marie Holmen. Her doctoral work is about risk in fish farming, where a lot of the research addresses risks related to conventional sea cages, especially the causal chain and risk of fish escape. She will finish her PhD degree in the spring of 2022, with the thesis *Safety in Exposed Aquaculture Operations – Strategies and methods for reducing risk.* Both likelihood and severity for the different events were assessed in the meetings and determined based on the frequency and consequence classes in Table 11 and Table 12.

Table 13: Hazardous events and current risk levels

Value	No. (i)	Hazardous event	Reference	Current risk level $RPN_{i,B}$	L_i	S_i
Personnel	1	Occupational accidents	RNNP, DSHA 14 (PSA, 2021)	7	5	2
	2	Man overboard	RNNP, DSHA 13 (PSA, 2021)	6	4	2
Environment	3	Fish escape	NS 9415 (Standard Norge, 2021)	6	4	2
	4	Littering to sea	No source	7	5	2
	5	Sea lice and disease spread - wild stock	(IMR, 2021c)	9	5	4
Material	6	Structural damage	RNNP, DSHA 8 (PSA, 2021)	6	4	2
	7	Breakdown of sea cage	(Standard Norge, 2021)	6	2	4
Fish	8	Compromised welfare	(IMR, 2021c)	8	4	4
	9	Fish death/increased mortality	(IMR, 2021b)	7	4	3
	10	Sea lice and disease spread	(IMR, 2021c)	8	5	3
	11	Loss of growth	(Yang et al., 2020)	5	4	1

6.4 Risk impact of key differences

This section corresponds to step 5 in the methodology description and determines the risk impact of each difference. Understanding the conventional system and associated risk picture is essential in order to identify the potential effects of the intended changes. Therefore, if the author's knowledge is limited, the argumentation will be supported by research and statistic (if available). The intention is to enhance the reliability of the assessments, particularly in the field of biology and fish welfare. This will hopefully reduce uncertainty and create a better basis for the decision-makers.

Further, when a key difference influences an existing hazard or event, the risk level for the conventional system will, in most cases, be shown in the *justification* column. The intention is to show the risk reducing/increasing potential of the particular change and, in this way, highlight the degree of influence. Documenting the risk reducing potential of a modification is helpful when future system changes are to be suggested or implemented, as this could ensure that previous modifications that had a large impact are not negatively affected. Likewise, highlighting changes with high risk impacts risk could help in prioritizing risk reduction measures or other decisions.

Analyzing the effect and determining the risk impact of each key difference is the core of the thesis's work. But since the worksheet became quite extensive, it was decided to attach it as an appendix. Thus, Appendix A shows the result.

6.5 Evaluation of change in risk

This section considers each hazardous event and assembles all the key differences that had an effect towards the particular hazardous event. The risk impact of the key differences and how they have changed the risk picture are discussed. Discussion of the result also addresses some risk reduction measures, as well as discussion about uncertainty. Uncertainty is mainly related to provided information, knowledge basis and to what degree changes in the assumptions will affect the result. The discussion further reflects on whether the overall change in risk is positive, negative or still the same. An overview of the overall change in risk is presented at the end of the section.

Out of 40 identified differences, 30 had a positive and/or negative effect and were assigned as key differences. Figure 35 provides an overview of the number of key differences influencing the various hazardous events and the amount of positive/negative effects. The key differences that had a risk impact with an ALARP level or higher were assigned with risk reduction measures.

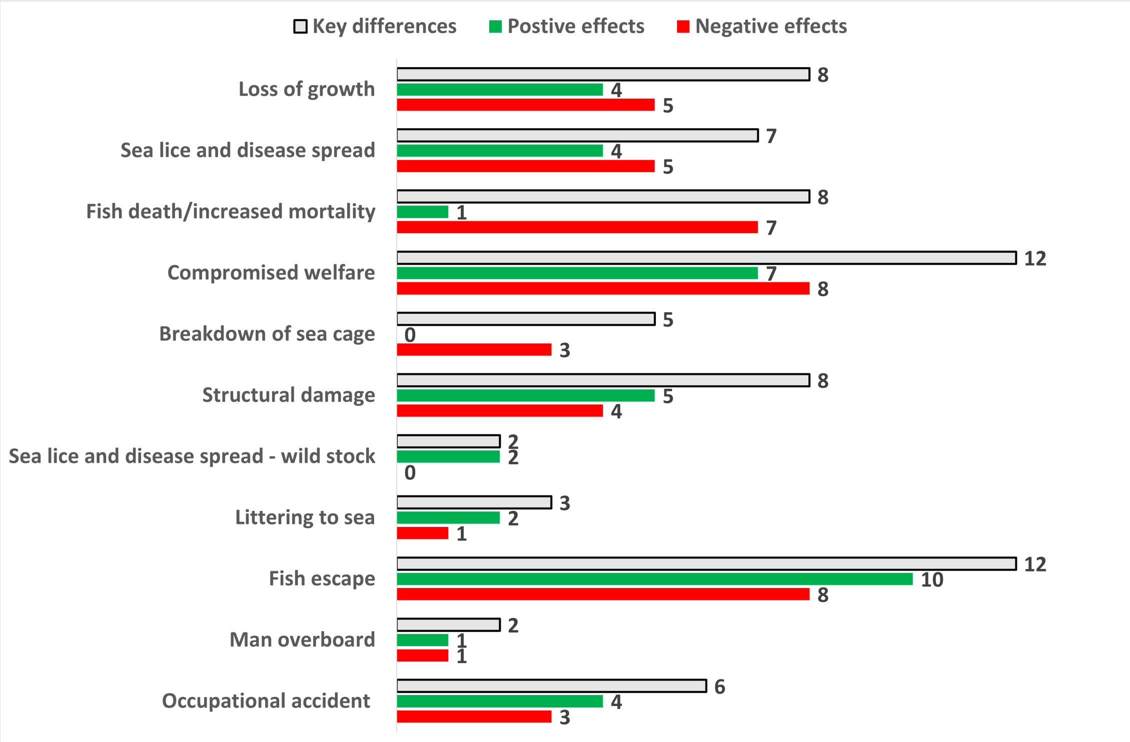


Figure 35: Number of key differences and negative/positive effects to each event

Additionally, ΔRisk_i is calculated according to formulas shown in Section 3. The numerical indicator shows the difference between the average risk impact of key differences and the current risk level of a particular hazardous event. It is nevertheless important to keep in mind that since ΔRisk_i is based on average risk impacts, many positive effects could obscure critical negative effects. Therefore, when observing the risk presentation, the single risk impacts and possible measures should have the foremost attention. ΔRisk_i is only used as a repetition of current risk and indicator of overall change in the risk picture.

Hazardous event E_1 - Occupational accidents

Table 14: Overview of key differences influencing E_1 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{1d}	No.	
2	S.B.	More remote	Neg.	7	1	Develop reliable and efficient emergency procedures with local rescue services.
3	S.B.	Environmental condition	Neg.	7	2	In the planning phase: Implement a procedure and model incorporated with allowable sea states/H_s, duration, historical weather data, and safety factors. The model should output a workable weather window which can be compared to site-specific forecasts and, thereby, provides decision support for safer execution of on-demand operations. Guachamin Acero et al. (2016) suggests a generic methodology that can be used for establishing operational limits and weather windows.
13	Tech.	Winch	Pos.	0		
13	Tech.	Winch	Neg.	5		
25	Tech.	Handrail	Pos.	5		
31	Oper.	Sea lice monitoring	Pos.	0		
37	Oper.	Net change	Pos.	5		
			$RPN_{1,A}$:	4.1		

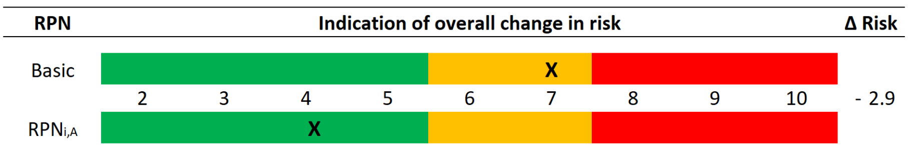


Figure 36: Indicators of overall change in risk for E_1 - Occupational accidents

Regarding occupational accidents, there were three key differences with negative effects, two with ALARP level 7. These were both related to changes at the system boundary and the operating condition of the sea cage. A more remote location and harsher weather conditions resulted in the two negative effects of increased emergency response time and shorter weather windows during on-demand operations. The positive effects are mainly related to the reduced amount of crane/capstan operations. The reduction is a result of less activity on the sea cage, both during normal operation and fewer on-demand operations (delousing, net change). The winch also removes the need for craning during bottom ring handling. Additionally, fewer rope interfaces on the handrail had positive effects in terms of cut injuries. Conventional sea cages experience a high ALARP level for occupational accidents, where many incidents are related to operations using cranes/capstans. Most positive effects and no key differences with a higher risk impact than the current risk level, resulting in $\Delta Risk_i$=-2.9, indicates an overall positive change in the risk picture for occupational accidents. However, the proposed risk reduction measures should be considered as these will enhance occupational safety in a more exposed site location. Changing the boundary condition is expected to reveal more harmful effects, as operations such as dead fish removal are unknown to the author and will occur outside the defined system boundary. It is not expected that negative effects will be predominant when extending the system boundary, but it creates uncertainty for the farmers' overall operational safety.

Hazardous event E_2 - Man overboard

Table 15: Overview of key differences influencing E_2 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{2d}	No.	
3	S.B	Environmental condition	Neg.	7		See risk reduction measure no. 2
37	Oper.	Net change	Pos.	5		
				$RPN_{2,A}$: 6		

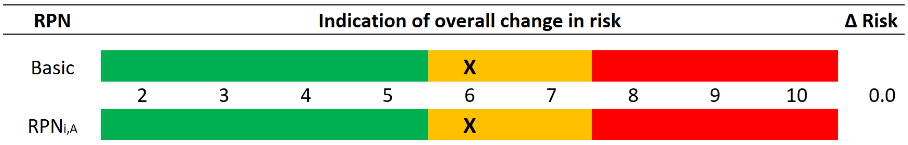


Figure 37: Indicators of overall change in risk for E_2 - Man overboard

The risk of man overboard accidents is still the same. Both identified effects were assessed to change the frequency by one level, thus not altering the risk picture. Although there is less activity at the sea cage, the likelihood of falling overboard during normal operation was reasoned to be the same. The main argument is that daily technical inspections still are to be executed. However, in terms of on-demand operations, a frequency reduction of falling overboard was found sufficient due to the decreased number of required operations. The positive effect was nevertheless equalized by the negative effect of harsher environmental operating conditions.

Hazardous event E_3 - Fish escape

Table 16: Overview of key differences influencing E_3 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{3d}	No.	
3	S.B	Environmental condition	Neg.	7		See risk reduction measure no. 2
[4, 6, 7]	S.B	External threats	Neg.	6	3	Install robust navigation lights adapted for the new environment (increased mechanical strength, higher positioned at buoys etc.) and appoint monitoring managers that can follow the shipping traffic alongside feeding control, either locally or/and at the remote operation center.
11	Tech.	Ceiling	Pos.	0		
11	Tech.	Ceiling	Neg.	7	4	Install four cameras for monitoring at each fifth of the extended side ropes, positioned 4m above the ceiling. The cameras should have a quick lock/release mechanism for efficient handling during elevating/descending of the net bag.
11	Tech.	Ceiling	Neg.	8	5	Design the zip-functionality with a secondary lock mechanism. An additional barrier is creating a written procedure/task list that must be used during the ceiling assembly.
17	Tech.	Mortality system	Pos.	0		

Table 16 continued on next page

Table 16: Overview of key differences influencing E_3 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{3d}	No.	
17	Tech.	Mortality system	Neg.	7	6	In order to be more durable against bites, install (from net bag exit) a semi-flexible wire reinforced PVC hose or a rigid HDPE pipe with a fixed bend directed towards the dead fish collection station. Further, with sufficient hose weight and stiffness, the net bag fastening can be pre-tensioned and large relative motions could also be avoided.
21	Tech.	Fastening of aux.eq.	Pos.	0		
21	Tech.	Fastening of aux.eq.	Neg.	7	7	Establish a reliable and standard knot to fasten relevant auxiliary equipment to the top rope and educate the personnel. Secondary, install eight 180° pan and tilt cameras positioned 4m below top rope, attached to side rope with a standard knot or with a customized fitting provided by the supplier.
21	Tech.	Fastening of aux.eq.	Neg.	7	8	Design net bag with fastenings loops dedicated for fastening of auxiliary equipment. The loops could be painted (e.g. blue) to make the fastening process even clearer.
22	Tech.	Collar - netting	Pos.	0		
23	Tech.	Expansion system - collar system	Pos.	0		
27	Tech.	Submerged net entries	Neg.	7	9	The bottom fixed cameras should be equipped with a 180° pan/tilt functionality. This enables monitoring of the bottom center. 4 to 8 cameras should be evenly disturbed around the cage and positioned approximately midway down the cross rope, starting from the ground rope. Risk reduction measure no. 4 applies to the net ceiling entry.
28	Oper.	Submerged as main state	Pos.	0		
28	Oper.	Submerged as main state	Pos.	0		
28	Oper.	Submerged as main state	Pos.	0		
28	Oper.	Submerged as main state	Pos.	5		
40	Oper.	Lift/lower the net-bag	Pos.	5		
			$RPN_{3,N}$:	3.7		

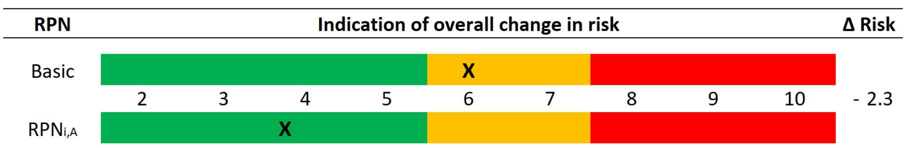


Figure 38: Indicators of overall change in risk for E_3 - Fish escape

The change in risk of fish escape seems to be positive. Ten key differences contribute positively, where several eliminated the possibility of certain escape events. In particular, the technical modification of the slack bottom ring suspension line, winch, and removal of the dead fish cone were important changes that removed/reduced the risk for several dominant escape events in conventional farming. Nevertheless, several key differences were determined to have negative effects on fish escape. The locking mechanism of the ceiling was the key difference with the highest risk impact. This key difference must have high priority in detailed design to prevent huge escape events or even total loss of cage population. The proposed proactive barrier is to design a secondary lock mechanism in the zipper and establish an assembly procedure. Measure no. 7 is a reactive barrier that could reduce the consequence through monitoring. Uncertainty of the results is considered quite low, particularly in the risk reduction spectrum: The assessment of positive effects is based on Føre and Thorvaldsen (2017), which documents hazards/causes for escapes in conventional fish farming and corresponding statistics on severity of the different escape events. On the other hand, more negative effects could be revealed when further decisions on the feeding and air dome system are taken. These systems are in an early concept phase, where provided information is limited, thus creating some uncertainty.

Further, the Midgard subsea system has introduced three new events that may lead to escaped fish:

- E_1^* = Hole in ceiling
- E_2^* = Zip not locked properly
- E_6^* = Hole in PVC hose

However, at this stage of product development, the new system has shown a promising change in the risk of fish escape by a predominance of positive effects and elimination of several main escape hazards. At the same time, $\Delta Risk_i$=-2.3 might be misleading in presenting the overall reduction potential. New events are introduced, and an additional five negative effects influence the risk of fish escape. Therefore, measures must be taken to ensure a positive development for the risk of fish escapes.

Hazardous event E_4 - Littering to sea

Table 17: Overview of key differences influencing E_4 and risk reduction measures

Key difference risk impact					Risk reduction measure
d	Type	Title	Effect	RPN_{4d}	No.
3	S.B	Environmental condition	Neg.	5	
18	Tech.	Cleaner fish components	Pos.	0	
25	Tech.	Handrail	Pos.	5	
			$RPN_{4,A}$:	3.3	

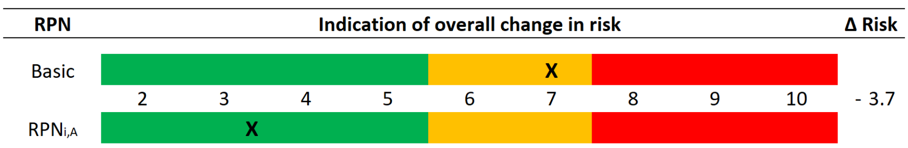


Figure 39: Indicators of overall change in risk for E_4 - Littering to sea

The local aquatic environment will be better safeguarded against pollution, as the risk of littering to sea has a very positive change. This positive change in risk reflects the reduced amount of equipment and activity at the floating collar, which are central causes of littering in conventional sea cages. Seven interfaces at the handrail are now removed, where the majority consisted of ropes for fastening auxiliary equipment. Ropes are a main hazard to littering in fish farming, and there are almost no ropes at the new system's floating collar. The new system had one negative effect on littering, however, compared to the same event in conventional farming, the frequency increased by only one level, and the associated risk was found to be low ($RPN_{4,3}$=5). The slight risk increase is nevertheless linked to risk reduction measure no. 2. Uncertainty is considered low, as provided information is found sufficient in this context. Areas where information is limited are mainly the air dome and the feeding system, which are not seen to introduce any hazard to littering due to their enclosed presence inside the net bag. Further, changes in assumptions are not seen to affect the result. Conclusively, the conventional system experience a high ALARP risk level for littering and the risk has undoubtedly changed positively with the planned modifications.

Hazardous event E_5 - Sea lice and disease spread - wild stock

Table 18: Overview of key differences influencing E_5 and risk reduction measures

Key difference risk impact					**Risk reduction measure**
d	Type	Title	Effect	RPN_{5d}	No.
2	S.B	More remote	Pos.	6	No measures found.
28	Oper.	Submerged as main state	Pos.	4	
			$RPN_{5,A}$:	5	

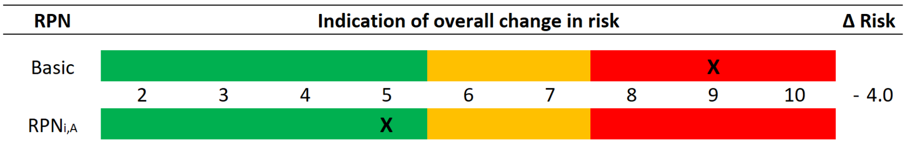


Figure 40: Indicators of overall change in risk for E_5 Sea lice and disease spread - wild stock

The intended changes for the Midgard subsea system significantly influence the risk of spreading sea lice and infectious diseases to the wild stock. Only two key differences influenced the risk, but both had positive effects and low risk impacts (relative to current risk). These key differences address the main hazards of transferring parasites and diseases to the wild stock, i.e. narrow fjords and the lice belt. As previously mentioned, the changes to a more remote location and submergence are the primary motivators for developing the Midgard subsea system. The key difference of submergence has the highest reduction potential, as submergence most likely will result in decreased infestation rates and consequently reduce pressure on migrating salmon. Sea lice spread to wild stock is the primary bottleneck in conventional farming for further expansion of the industry, and the subsea system shows promising effects in reducing the spread risk and safeguarding the wild stock.

Hazardous event E_6 - Structural damage

The conventional system has a low ALARP risk level in terms of structural damage, and with the Midgard system's intended changes, the risk will most likely decrease even more. The positive effects result in an overall positive change in the risk picture, but there are key differences with ALARP levels that must be considered. The risk reduction measures of d=23 are linked to conflicts with propellers due to spooling out excessive lengths of rope, but the latter measure might involve a too high investment cost considering a moderate risk level ($RPN_{6,23} = 6$). Risk tolerability could, in this situation, be guided by the ALARP principle, as suggested in Section 6.1.3. The positive change in risk is mainly due to submergence and consequently sheltering the auxiliary equipment from negative surface events, which is a central hazard to tear and/or fatigue damage in the conventional system. Additionally, submergence reduces biofouling and consequently leads to two positive effects on structural damage (d=28 and d=38). However, some external interfaces are not submerged, leading to an ALARP risk impact from key difference no. 1. Lack of information on the feeding system and the air dome might create some uncertainty in the result. However, the positive change in risk still seems to be a reasonable presentation of the Midgard subsea system's influence on the risk of structural damage.

Table 19: Overview of key differences influencing E_6 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{6d}	No.	
1	S.B	External interface change	Neg.	6	10	Suspend the feeding pipe (negatively buoyant when filled with water) in the floating collar steel bracket (1.3), 10m below the water surface. The tube will experience a 30° net entry angle at a ceiling depth of 25m. If using traditional flexible feeding pipes (3.3.1), low entry angles might break the soft polyethylene pipes, a problem that would magnify when elevating the net bag. A measure is thus a customized pipe with a fixed/stiff bend that ensures straight entry. The pipe must have neutral buoyancy. Lastly, a traditional PE transition sleeve should be applied to connect the two pipes, thus avoiding conflicts with the collar during elevation (the sleeve has a threaded connection, enabling easy disconnection). The sleeve should be located close to the suspension point. See Figure 47.
3	S.B	Environmental condition	Neg.	7		See risk reduction measure no. 2
13	Tech.	Winch	Neg.	6	11	Establish a periodic maintenance plan for the winches.
21	Tech.	Fastening of aux.eq.	Pos.	0		
23	Tech.	Expansion system - collar system	Neg.	6	12	Clearly specify a maximum length of slack rope in the winching procedure. Another measure is to equip the winch with a load cell/cable tension sensor that deactivates the "down-button" (at the remote controller) 2-3 seconds after zero tension. The remote controller should have an override button (in case of conflicts).
28	Oper.	Submerged as main state	Pos.	5		
28	Oper.	Submerged as main state	Pos.	5		
37	Oper.	Net change	Pos.	0		
39	Oper.	Net cleaning	Pos.	5		
40	Oper.	Lift/lower net bag	Neg.	5		
			$RPN_{6,A}$:	4.5		

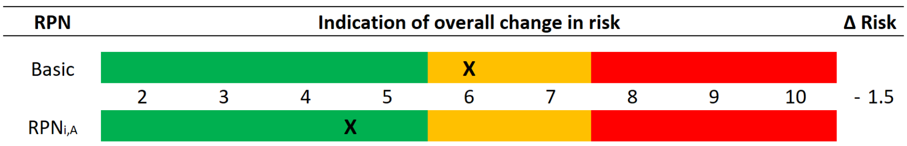


Figure 41: Indicators of overall change in risk for E_6 - Structural damage

Hazardous event E_7 - Breakdown of sea cage

Table 20: Overview of key differences influencing E_7 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{7d}	No.	
3	S.B	Environmental condition	Neg.	7		See risk reduction measure no. 2
[4, 6, 7]	S.B	External threats	Neg.	6		See risk reduction measure no. 3
35	Oper.	Daily inspection	Neg.	6	13	Modify technical inspection procedures, emphasizing critical components and providing a detailed checklist that should be used before harsh weather/storms. Optimize periodic maintenance or replacement intervals for critical components. Another measure is to integrate cameras into the handrail, pointing down towards each mooring line, enabling partial monitoring of technical equipment.
			$RPN_{7,A}$:	6.3		

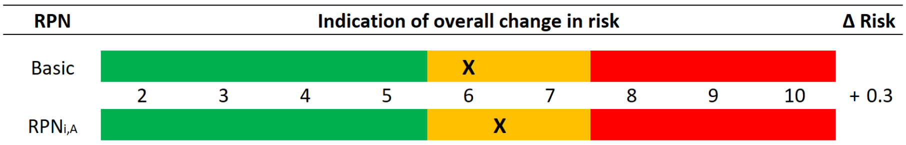


Figure 42: Indicators of overall change in risk for E_7 - Breakdown of sea cage

The change in risk of a breakdown event is undoubtedly negative. Three key differences had negative effects on the hazardous event and impacted the risk with ALARP risk levels. Since all risk impacts were exclusively negative, the risk of structural breakdown will certainly increase with the Midgard subsea system. All the key differences are related to a changed operational condition of a more remote location and harsher environment. The on-demand operations and daily technical inspection are carried out under the same weather restrictions and requirements as before. And, with harsher weather and shorter weather windows, the likelihood of structural breakdown increases (see analysis of d=3 and d=35 for more specific descriptions). Additionally, the more remote location will most likely increase the threat of heavier shipping traffic and submarines. The measure of installing cameras in the handrail to compensate for the reduced availability of on-cage inspections might be expensive. However, the consequence of a structural breakdown is severe, and the different measures should be strongly considered. Changing the assumption (see Section 6.1) by locating the sea cage within rocks and islets is a measure that probably will reduce the risk and thus influence the result. Other assumptions are not seen to affect the result and provided information on the degree of exposure is found sufficient.

Hazardous event E_8 - Compromised welfare

Table 21: Overview of key differences influencing E_8 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{8d}	No.	
3	S.B	Environmental condition	Pos.	0		
3	S.B	Environmental condition	Neg.	8		See risk reduction measure no. 2

Table 21 continued on next page

Table 21: Overview of key differences influencing E_8 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{8d}	No.	
11	Tech.	Ceiling	Neg.	8	14	Design an air dome with an apex height of 1 meter, allowing the salmon to partly express normal surface/jumping behaviour although submerged. The submerged concept developed by NRS (2019) has an apex height of 1m and could be used as inspiration.
14	Tech.	Air dome	Neg.	6	15	Install the air supply pipe with as few turns and steep angles as possible. By the net bag entry, the air pipe should be weighted or stiff enough to prevent breaking in this area. Optimize air compressor maintenance interval and install a backup compressor. The air supply inside the net bag is suggested to be flexible. See risk reduction measures no. 7 and no. 8 regarding fastening of air dome. Secondary, install 2-4 echo sounders to monitor swim bladder fullness.
24	Tech.	Interface, expansion system - net bag	Pos.	5		
28	Oper.	Submerged as main state	Pos.	4		
28	Oper.	Submerged as main state	Neg.	9	16	The site examination prior to farm installation should be given high priority and provide reliable/accurate data on the submerged environmental condition. Evaluation of results should gain even more attention and be supported with a detailed risk assessment to provide better decision support for farm deployment. Wrong decisions might result in severe consequences for both fish welfare and production. Secondary, develop farming strategies that seek optimal environmental conditions (temp./O_2) by elevating/lowering the net bag throughout the production cycle. The strategy must then be based on a thorough site examination and available data/experience regarding maximum exposure time at various depths before lice infestation risk becomes too high. In this way, a favorable balance between lice infestation risk and environmental conditions could potentially be achieved.
29	Oper.	Start feeding	Neg.	7	17	Design a feeding system which ensures optimal spreading of the pellets. For instance: A circular pipe located midway from the cage center (diameter=25m), distributing the pellets evenly around the cage. Further, such a configuration might result in less interaction between feeding fish and those gulping air. See risk reduction measure no. 7 in terms of monitoring emaciated fish.
31	Oper.	Sea lice monitoring	Pos.	0		
31	Oper.	Sea lice monitoring	Neg.	7	18	Implement monitoring with individual based OWIs in operation strategies proposed in risk reduction measure no. 16.
32	Oper.	Fish welfare monitoring - OWI usage	Neg.	8	19	Enhance fish welfare monitoring by integrating two 180° pan and tilt cameras in the air dome, pointing downwards. Risk reduction measure no. 7 and no. 9 also applies.

Table 21 continued on next page

Table 21: Overview of key differences influencing E_8 and risk reduction measures

Key difference risk impact					Risk reduction measure
d	Type	Title	Effect	RPN_{8d}	No.
34	Oper.	Cleaner fish	Pos.	5	
38	Oper.	Delousing	Pos.	6	No measures found besides them already applied during delousing.
39	Oper.	Net cleaning	Pos.	5	
40	Oper.	Lift/lower the net-bag	Neg.	6	See risk reduction measure no. 20
			$RPN_{8,A}$:	5.6	

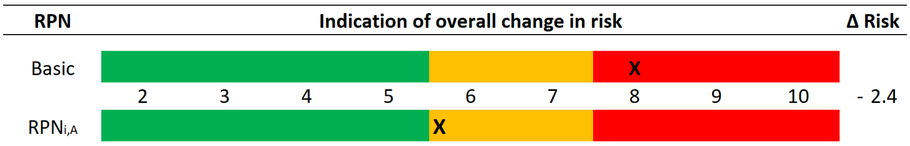


Figure 43: Indicators of overall change in risk for E_8 - Compromised welfare

The result shows many positive changes in the risk picture of hazardous event no. 8. Many key differences decrease the risk by reducing the frequency of physical handling/crowding and the likelihood of other harmful events, such as hypoxia. Furthermore, the sea lice camera influenced positively by removing the need for manual handling, and submergence eliminated the likelihood of adverse surface events.

Generally, most of the risk impacts were lower than the current risk level, and the relative overall change in risk of $\Delta Risk_i$=-2.4 might indicate a positive change in the risk picture. However, in this case, the overall change is misleading, and as emphasized earlier, the single risk impacts must have the primary attention. $RPN_{8,A}$=5.6 comprises seven positive and eight negative effects, where the positive obscure the negative ones. Several of the positive effects did not address issues involving a large risk to fish welfare. For instance, the positive effects of d=3, d=24, d=31, d=34, and d=39 influenced events that all had RPN=6 (low ALARP) in the conventional system. On the other side, many of the negative effects are related to new hazardous events (shown below), and some effects increase the risk to a much larger extent compared to the risk reduction potential of the abovementioned key differences.

- E_3^* - Jumping denied
- E_4^* - No air access

A risk that has increased considerably is the operational risk in terms of fish welfare monitoring. OWIs are applied without any problem in conventional farming, but with the Midgard subsea system, most of the animal based OWIs are found to have reduced operability. This will undoubtedly increase the likelihood of reduced welfare. Analysis of d=28 also revealed a significant increase in the likelihood of sub-optimal environmental conditions at the intended operational depth (20-30m), which with a high probability will deteriorate fish welfare throughout a production cycle. The author's knowledge basis is limited in this context, but most of the assessments are based on scientific research, and the reader is advised to see the worksheet for further details. Besides this uncertainty, the results show a predominance of negative effects with a substantial impact on fish welfare, and measures and strategies must be carefully considered in order to protect the fish from suffering and sub-optimal environmental conditions.

Hazardous event E_9 - Fish death/increased mortality

Table 22: Overview of key differences influencing E_9 and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	RPN_{9d}	No.	
3	S.B	Environmental condition	Neg.	8		See risk reduction measure no. 2
28	Oper.	Submerged as main state	Neg.	8		See risk reduction measure no. 16
29	Oper.	Start feeding	Neg.	7		See risk reduction measure no. 17
31	Oper.	Sea lice monitoring	Neg.	7		See risk reduction measure no. 18
32	Oper.	Fish welfare monitoring - OWI usage	Neg.	8		See risk reduction measure no. 19
35	Oper.	Daily inspection	Neg.	7		See risk reduction measure no. 13
38	Oper.	Delousing	Pos.	6		No measures found besides them already applied during delousing.
40	Oper.	Lift/lower the net-bag	Neg.	7	20	Add and evenly distribute small floaters to the ceiling to avoid sinking when unzipped. Secondary, create a procedure for net ceiling removal.
			$RPN_{9,A}$:	7.3		

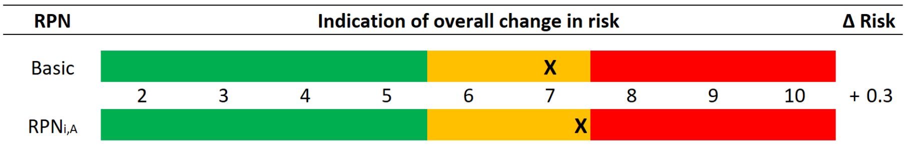


Figure 44: Indicators of overall change in risk for E_9 - Fish death/increased mortality

The risk of fish death has undoubtedly increased. Out of eight contributing key differences, only one influenced positively. This positive risk impact is related to the reduced frequency of delousing processes. The remaining seven risk impacts had equal or higher risk levels compared to the current risk level, resulting in an average risk impact higher than the present risk of experiencing increased mortality. This indicates a very unfortunate change in the risk of fish death, and also reflects upon the negative effects on compromised welfare (E_8). Fish death is often a consequence of a disease outbreak or prolonged suffering due to compromised welfare. Therefore, many of the negative effects on compromised welfare and disease spread also increased the risk of fish death. On the other hand, the positive effects that reduced the risk of compromised welfare and sea lice/disease spread were not found to similarly reduce the risk of fish death. As previously mentioned, most of the positive effects on compromised welfare had limited risk reduction potential due to low ALARP risk levels in conventional farming. Further, most of the positive effects on sea lice/disease spread were related to reduced sea lice pressure, and according to NVI (2022b), only severe infestations and wounds might be fatal for the fish. Fish death in the context of sea lice is mainly due to delousing treatments, which has been accounted for in the positive effect from key difference 38. In other words, the negative effects of compromised welfare and lice/disease spread influenced the risk of fish death much more than the positive ones.

Most of the negative effects are related to lack of control on fish welfare due to reduced operability of group based OWIs and less sampling of individuals, as well as the high mortality that potentially could be experienced with sub-optimal conditions in a submerged environment. Further, the negative effect of insufficient start feeding might give rise to an increased occurrence of loser fish. All these abovementioned effects are assigned with risk reduction measures in E_8 - Compromised welfare. Additionally, the new system has introduced the two following hazardous events.

- E_7^* - Disconnection of net bag
- E_9^* - Fish caught in the ceiling

As for E_8 - Compromised welfare, the result involves some uncertainty due to a lack of knowledge in biology and veterinary research. However, the negative effects and measures should be taken seriously, as almost all key differences negatively impact the risk through inadequate operational control. The potential disconnection of the net bag caused by less technical inspections, partly welfare monitoring through the underwater cameras, and fish trapped in the ceiling are good examples of this.

Hazardous event E_{10} - Sea lice and disease spread

Table 23: Overview of key differences influencing E_{10} and risk reduction measures

Key difference risk impact					Risk reduction measure	
d	Type	Title	Effect	$RPN_{10,d}$	No.	
1	S.B	External interface change	Neg.	7		See risk reduction measure no. 10
2	S.B	More remote	Pos.	7		No measures found.
16	Tech.	Camera system	Neg.	7	21	Equip bottom fixed cameras with wiper blades.
21	Tech.	Interface, fastening of aux. eq.	Neg.	7		See risk reduction measure no. 7 and no. 8
28	Oper.	Submerged as main state	Pos.	5		
28	Oper.	Submerged as main state	Pos.	5		
31	Oper.	Sea lice monitoring	Pos.	5		
31	Oper.	Sea lice monitoring	Neg.	7		See risk reduction measure no. 18
32	Oper.	Fish welfare monitoring - OWI usage	Neg.	8		See risk reduction measure no. 19
			$RPN_{10,A}$:	6.4		

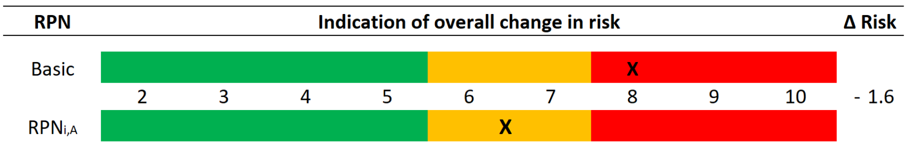


Figure 45: Indicators of overall change in risk for E_{10} - Sea lice and disease spread

The average risk impact is far lower than the current risk level of spreading sea lice or diseases in conventional sea cages. However, the result has a predominance of negative effects, and the change in risk is not necessarily positive. Additionally, E_{10} comprises two independent events, i.e., sea lice spread and disease spread, and it can be discussed whether the event should have been separated into two events. The hazardous event was initially stated this way to make the work more efficient. However, the analysis of key differences clearly states whether a particular effect influences the risk to lice or disease spread. Out of nine risk impacts, three key differences influenced the risk of spreading disease in the cage. The submergence had a positive effect by reducing biofouling and consequently reducing the likelihood of harmful AGD outbreaks, while removing the manual sampling of the fish during lice counting increased the risk of disease outbreak. Despite these identified risk impacts, there could be more diseases influenced by submergence or other key differences, and since knowledge is limited in this context, the change in risk of disease spread involves uncertainty.

The remaining six key differences influenced the risk of sea lice spread. As previously mentioned, decreasing sea lice pressure is the main motivation of the Midgard subsea system, and the modifications have shown promising risk reduction potential. The submergence had, as expected, a significant influence on the risk, and has reduced the risk from an unacceptable risk level to $RPN_{10,28}$=5. However, this considerable risk reduction potential is to some degree held back by three negative effects with high ALARP risk levels. More precisely, this refers to key differences no.1, 16, and 21, which all relate to events that cause a need for repair and elevation of the net bag, thus increasing the risk of lice infestation. All three risk impacts are assessed to RPN=7 and are based on the assumption that sea lice can adapt and remain after submergence, as stated in Section 6.1. The result is, in other words, sensitive to this assumption.

Overall, the risk of sea lice spread has changed positively. But, how risk has changed regarding disease spread involves a lot of uncertainty, and no statement on whether the overall risk has decreased or increased will be taken. In other words, the overall change in risk of disease spread is assessed to be unknown. The single risk impacts nevertheless show how three key differences change the risk of disease spread.

Hazardous event E_{11} - Loss of growth

Table 24: Overview of key differences influencing E_{11} and risk reduction measures

Key difference risk impact					Risk reduction measure
d	Type	Title	Effect	$RPN_{11,d}$	No.
1	S.B	External interface change	Neg.	9	See risk reduction measure no. 10
14	Tech.	Air dome	Neg.	6	See risk reduction measure no. 15
15	Tech.	Feeding system	Pos.	0	
24	Tech.	Expansion system - net bag	Pos.	5	
28	Oper.	Submerged as main state	Pos.	5	
28	Oper.	Submerged as main state	Neg.	8	See risk reduction measure no. 16 and 17.
29	Oper.	Start feeding	Neg.	7	See risk reduction measure no. 17
30	Oper.	Feeding	Neg.	8	See suggestion of new camera configuration proposed in risk reduction measures no. 9, no. 13 and no. 21.
38	Oper.	Delousing	Pos.	6	No measures found besides them already applied during delousing.
			$RPN_{11,A}$:	6	

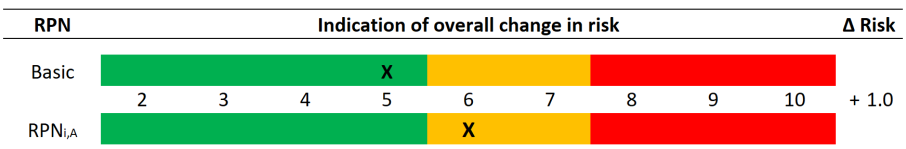


Figure 46: Indicators of overall change in risk for E_{11} - Loss of growth

In terms of losing growth, the change in risk is clearly negative. Although four key differences had positive effects, the risk has certainly increased due to five negative impacts with relatively high risk levels compared to the current risk level (RPN=5). The positive effects did not address issues with high risk levels in conventional farming, i.e., moderate risk reduction potential. On the other hand, there were three negative impacts with red risk levels, where the most concerning key difference is no. 28. Although submergence is positive in terms of biofouling and thus reducing the frequency of events with reduced water exchange, Warren-Myers et al. (2022) documented a harvest size of almost half the weight of the expected 5kg. The reader is advised to see the worksheet for more details. Furthermore, the risk impact of key difference no. 30 reflects on the inadequate feeding control experienced through the intended camera configuration. These impacts, together with removing the hand feeding operation (d=29) and the increased likelihood of broken feeding pipes (d=1), prove that the Midgard subsea system most likely will experience an adverse change in fish growth. This will further result in prolonged production and finical loss for the farming company. There is some uncertainty related to the feeding system and strategy conducted by Warren-Myers et al. (2022). Limited control of feed intake and a feed dispersion area that was smaller than control cages might have been contributing factors to poorer growth in submerged cages (O. Folkedal, personal communication, April 28, 2022). In other words, the Midgard subsea system can potentially mitigate the adverse change in risk by optimizing the feeding system and improving the monitoring capability. Risk reduction measures no. 9, 13, 17, and 21 are relevant for this purpose. Apart from the uncertainty related to the feeding setup in Warren-Myers et al. (2022), the knowledge basis is found to be sufficient due to experience in the feeding operation, and changes in the assumptions are not seen to affect the result.

Overview of overall change in risk

Table 25 present an overview of the total change in risk, determined in the previous presentations and discussions. Uncertainty as to whether the risk change is valid has also been discussed and is shown by denoting either *low*, *medium*, or *high* to the hazardous event.

Table 25: Overall change in risk

Value	E_i	Hazardous event	Change in risk	Uncertainty
Personnel	1	Occupational accidents	Positive	Low
	2	Man overboard	No change	Low
Environment	3	Fish escape	Positive	Medium
	4	Littering to sea	Positive	Low
	5	Lice/disease spread - wild stock	Positive	Low
Material	6	Structural damage	Positive	Medium
	7	Breakdown of sea cage	Negative	Low
Fish	8	Compromised welfare	Negative	Low
	9	Fish death/increased mortality	Negative	Low
	10	Sea lice spread	Positive	Low
	10	Disease spread	Unknown	High
	11	Loss of growth	Negative	Low

Overview of risk reduction measures

Figure 47 provides an overview of the technical risk reduction measures. The drawing illustrates the descriptions in the preceding tables and intends to communicate the proposed measures more clearly. Measures not shown in the drawing are operational measures, and the reader is advised to see the tables for descriptions. The blue color indicates ScaleAQ's design intentions regarding auxiliary equipment.

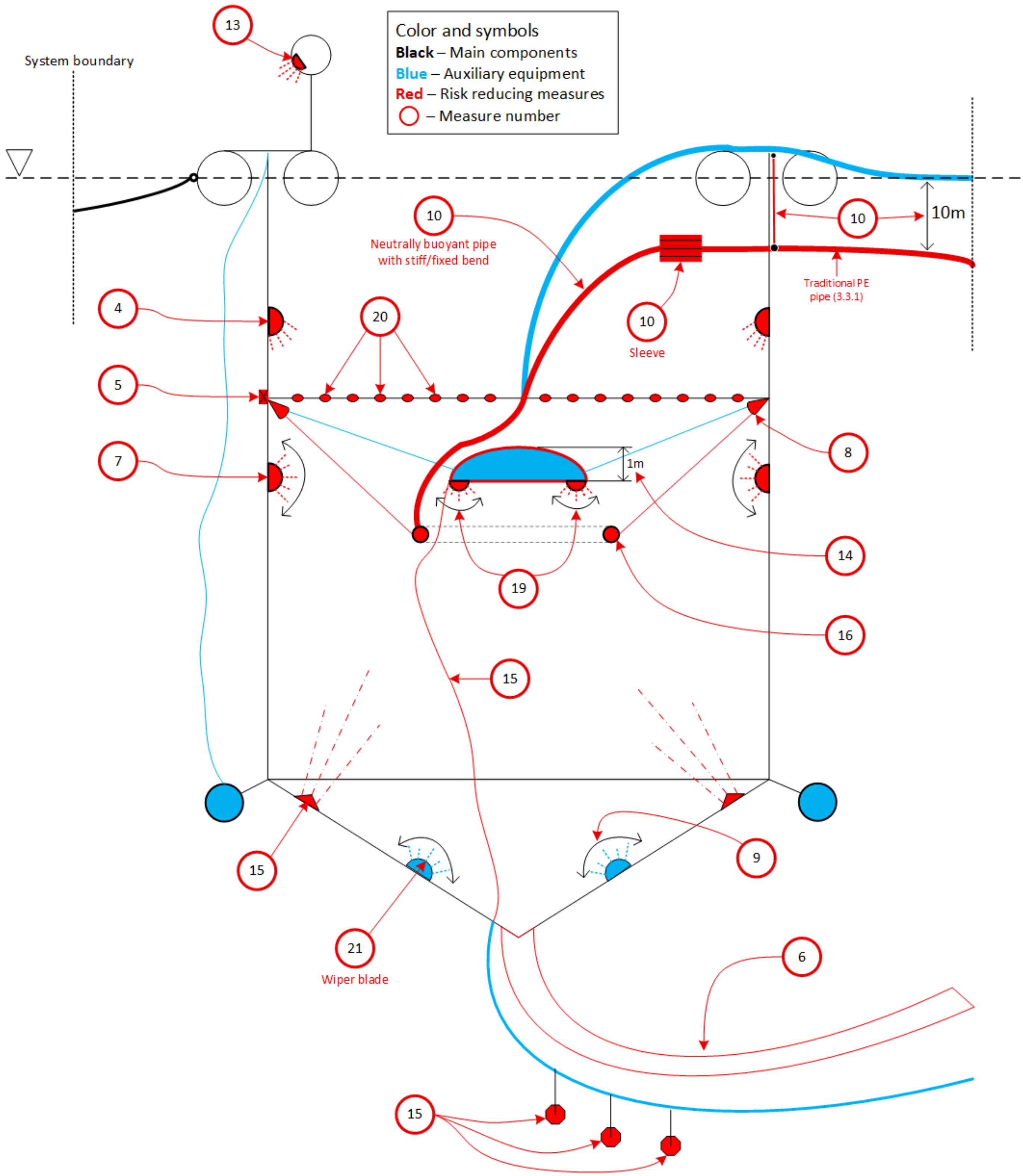


Figure 47: Technical risk reduction measures

6.6 Overview of new hazards/events

Table 26 presents an overview of the new hazardous events introduced by the Midgard subsea system. The summary shows the associated risk and the corresponding key difference that gave rise to the new event.

Only events that were uniquely new or assessed as almost impossible to occur in the conventional sea cage were listed. If more precise event descriptions had been used, such as specifying which operational condition the event occurs at, almost every identified effect had been linked with a new hazardous event due to the new in-depth operating condition. Therefore, for the purpose of this analysis, only distinctive events were marked as new events. The reader is advised to read the analysis worksheet or discussions above for more details regarding these events.

Table 26: New hazards/events introduced by the new system

		Assessed risk			**Key difference and risk reduction measures**		
E_i^*	**Hazard/event**	RPN	L	S	d	Title	Measure no.
1.	Hole in ceiling	7	4	3	11	Ceiling	4
2.	Zip not locked properly	8	4	4	11	Ceiling	5
3.	Jumping denied	8	5	3	11	Ceiling	14
4.	No air access	6	3	3	14	Air dome	15
5.	Dirty camera lenses	7	5	2	16	Camera system	21
6.	Hole in PVC hose	7	4	2	17	Mortality system	6
7.	Disconnection of net bag	7	2	5	35	Daily inspection	13
8.	Side ropes on propeller	5	4	1	40	Lift/lower net bag	N/A
9.	Fish caught in the ceiling	7	4	3	40	Lift/lower net bag	20

7 Discussion

It is important to mention that the main discussion of the result and associated uncertainty is carried out in the previous section (Section 6.5). Thus, this section provides an overall discussion of the applied method and the result.

7.1 Methodology

The Change Analysis's core principles described by Rausand and Haugen (2020) are applied and reflected throughout the thesis work. But, as introduced in Section 1, the book's method description is somewhat limited, and a part of the thesis work was to adapt the method to the thesis objectives. The final approach is found sufficient in analyzing the risk impact of the various key differences. However, the workflow had some weaknesses that should be kept in mind and potentially revised if the method is to be replicated.

First, the main worksheet (Table 2) was sometimes found lacking in terms of highlighting the hazards, causes and consequences related to an effect. The selected hazardous events E_i and E_i^* were the only events listed in the worksheet, whereas the various enabling events and consequences in the accident scenario of E_i were described and accounted for in the justification column. However, if there had been two additional columns for causes and consequences, the extent of justification could potentially be reduced or even removed. Such a configuration would give the reader a holistic understanding of the risk impact more efficiently compared to the current approach, where it is required to read the justification before understanding the determined likelihood and consequences. However, as the reasoning behind the effect and associated risk was not always easy to express in short phrases, the justification column was found to be the most convenient approach. One column for justifying the effect and additional columns for hazards, causes, and consequences could have been used, but since the analysis aimed to consider both positive and negative impacts, the worksheet would most likely be too large to handle.

Secondary, step 6 of the analysis presented two indicators intended to provide an impression of the overall change in risk of a hazardous event E_i. More precisely, these indicators were the combination of average risk impact ($RPN_{i,A}$) and the difference between average impact and current risk level ($\Delta Risk_i$). The idea was to provide a numerical indication of movement in risk within the range of possible risk levels, RPN=[2,10]. However, the indicators were sometimes found to be misleading and unsuitable for their purpose. Firstly, few positive effects with low RPN values can obscure many negative effects and ΔRisk becomes misleading, especially if the current risk level is of a high RPN value. In other words, the contributing key differences might be a majority of negative effects, and in the case of a high $RPN_{i,B}$, the $\Delta Risk_i$ might indicate a positive change in risk. In the worst case, if a particular hazardous event is solely affected by negative effects with lower risk impacts than $RPN_{i,B}$, the $RPN_{i,B}$ will indicate a positive change even though the risk impact is undoubtedly negative. In simple terms, modifications to a system that solely have negative effects on a hazardous event will inevitably increase the risk and contribute to a negative change in the risk picture. The numeric indicators were to some degree useful as long as attention was paid to the overview of all key differences, which denoted if the differences had a negative or positive effect on the risk. If the work is to be replicated, and if the analyst wants to apply indicators on the overall change in risk, the author suggests that a risk matrix such as the one in Figure 48 is applied. The matrix will then illustrate the current risk level and all risk impacts. Compared to using average risk impact, the risk matrix tabular is most likely a more suitable indicator of overall change in risk. Unfortunately, the author did not have time to substitute the numerical indicators and revise the master thesis methodology and result.

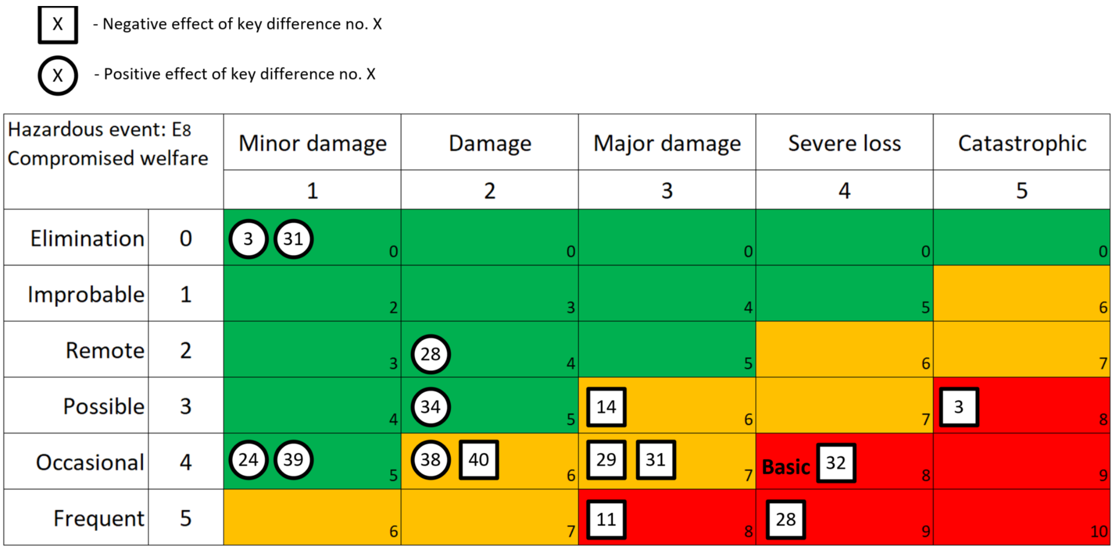


Figure 48: Risk matrix as alternative indicator on overall change in risk

The input to the matrix is based on risk impacts to E_8 - Compromised welfare. Resulting $RPN_{i,A}$ and $\Delta Risk_i$ for hazardous event E_8 was a good example of the pitfall that may be experienced using the numerical indicators, and the reader is advised to see Section 6.5 for more details.

Nevertheless, $RPN_{i,A}$ and $\Delta Risk_i$ were never decisive for the analysis result, as they were, as stated many times, only indicators. The main objective of the thesis was to determine the risk impact of every single key difference, and if an overall change in risk was to be evaluated, it had to be based on a holistic discussion of all risk impacts and associated uncertainty. Evaluation of overall change based on a holistic consideration of risk impacts is carried out, where a summary is presented in Table 25.

Lastly, the column designated for risk reduction measures in worksheet no. 3 (Table 3) could have been modified to include two additional columns to show if a particular risk reduction measure addressed the causal or consequence spectrum. In other words, denote if the measure would reduce the frequency or the severity of the given event, or in a barrier management perspective: Distinguish between proactive or reactive barriers. The author chose to prioritize space for numbering and description. Nevertheless, when applicable, the type of measure was mentioned.

Despite the discussed weaknesses, the methodology applied is considered suitable for the thesis's objective, that is, to identify differences between the systems and determine their risk impacts. The integration of the guiding principle in NS 5814 is also considered to be successful. And since NS 5814 is among the governing standards in Norwegian aquaculture, the generic methodology description is found to be a good way of performing change analyses to other modified sea cage designs.

7.2 Overall discussion on result

Section 6.5 has discussed the change in risk of each hazardous event E_i. The section assembled all relevant key differences, highlighted the ones with a large risk impact and proposed risk reduction measures. The reader is advised to see Section 6.5 regarding discussion of change in risk of a particular hazardous event E_i. In this overall discussion section, the author wants to recapitulate and emphasize the importance of step 5 - *Risk impact of differences*. The analysis worksheet has described the effect of each key difference, both positive and negative, and determined the corresponding risk impact. As a result, the completed worksheet provides a systematic presentation of how, and to what degree, every key difference will affect one or more values. Step 5 is the core of the thesis work, and the author wants to call attention to some critical differences. The list below shows these. As the list shows, a key difference might impact several hazardous events. Thus, it is of paramount importance to focus on the worksheet in order to understand the total effect of a key difference. Comprehension of effect and resulting risk impact is also crucial for making good decisions and understanding the intention of the proposed risk reduction measures.

- **Key difference no. 1 - External interfaces**
  Increased risk of 3 hazardous events.
- **Key difference no. 3 - Environmental condition**
  Increased risk of 8 hazardous events.
- **Key difference no. 11 - Ceiling**
  Increased risk of 3 hazardous events.
- **Key difference no. 14 - Air dome**
  Increased risk of 2 hazardous events.
- **Key difference no. 17 - Mortality system**
  Increased risk of 1 hazardous event.
- **Key difference no. 21 - Interface: Fastening of auxiliary equipment**
  Increased risk of 3 hazardous events.
- **Key difference no. 27 - Interface: Submerged net entries**
  Increased risk of 1 hazardous event.
- **Key difference no. 28 - Normal operation: Submerged as main state**
  Increased risk of 3 hazardous events.
- **Key difference no. 29 - Normal operation: Start feeding**
  Increased risk of 3 hazardous events.
- **Key difference no. 30 - Normal operation: Feeding**
  Increased risk of 1 hazardous events.
- **Key difference no. 31 - Normal operation: Sea lice monitoring**
  Increased risk of 3 hazardous events.
- **Key difference no. 32 - Normal operation: Fish welfare monitoring - OWI usage**
  Increased risk of 3 hazardous events.
- **Key difference no. 35 - Normal operation: Daily inspection**
  Increased risk of 2 hazardous events.
- **Key difference no. 40 - On-demand operation: Lift/lower the net bag**
  Increased risk of 3 hazardous events.

The author does not want to rank the listed key differences as they negatively affect all values. But, it is evident that the majority is operational differences, where central hazards were found to be sub-optimal environmental conditions and a poor camera configuration leading to inadequate control of feeding and fish welfare. However, the list also consists of several key differences related to the technical aspect and the boundary condition of the system, and the reader is advised to see step 5 for further details. The list only intends to be a repetition of differences that had serious risk impacts, where corresponding risk reduction measures or other decisions will be of significant importance in order to safeguard the predefined values and reduce the risk to ALARP.

One main limitation of the Change Analysis is that it requires a thorough knowledge of the system and the risk issues of the basic system (Rausand and Haugen, 2020). Thus, a lot of effort was put into describing the conventional system in Section 4, as well as understanding the risk picture in conventional fish farming through the literature review in Section 2. However, in terms of system description, the result would have been different if another system configuration had been chosen. As introduced in Section 4, there are numerous possible sea cage configurations in Norwegian fish farming. Several net bag designs and sub-suppliers of auxiliary equipment are available on the market. For instance, some farmers use a mortality system integrated to the barge, whereas others winch a large scoop net to collect the dead fish. Furthermore, there are several different types of bird protection systems, spreaders, and operational strategies (e.g., not all farmers monitor through underwater cameras, and it is not required to farm with cleaner fish). However, this study's defined system description is considered reasonably conventional. It is nevertheless important to keep in mind that any substitution of main components, auxiliary equipment, interfaces, and operations will be very sensitive to the result of the analysis.

The Midgard subsea system also possesses technical and operational aspects that, to a large degree, will influence the result if changed. Firstly, the strict operational strategy of elevating the net bag only in case of on-demand operations/emergencies can potentially be revised to allow more freedom. Some farmers might prefer to produce in the upper position in the last months before harvest to optimize growth or partly operate in the surface during the winter months when lice pressure is low. However, such operational strategies will result in a different risk picture compared to the one obtained in this analysis, especially in terms of risk to fish welfare and personnel. The risk of lice infestation will certainly increase. At the same time, the risk of compromised welfare would most likely be reduced due to enhanced welfare monitoring and better environmental conditions. The risk of occupational accidents might increase as more time would be spent on the floating collar. Secondary, as introduced, some of the auxiliary equipment are at a conceptual/idea design level. Thus, limited information was available, particularly related to the air dome and the feeding system. If more information on these products had been known, additional hazards could have been revealed (e.g., wear towards the net bag). At the same time, the execution of the change analysis has revealed certain hazards, where corresponding risk reduction measures might be helpful in the design process of these products. For instance, the proposed measures of customized loops for fastening the air dome and spreader, as well as integrating cameras to the air dome, are design changes that promote enhanced fish welfare and reduced risk of fish escapes.

The following list discuss some aspects with the analyzing process in step 5.

- **Inclusion of basic system risk**
  When a key difference affected an existing hazard or event in the conventional system, the author decided to include a short assessment of the current risk level at the particular event. The intention of this was to get a better understanding of the risk reduction (or increasing) potential of the key difference. The methodology description in Section 3 clearly emphasizes the importance of knowledge about the basic system and associated risk picture in order to successfully identify effects and determine risk impacts. However, assigning basic risk levels in the justification column was not a requirement. Nevertheless, the action provided the author with a better overview of the risk changing potential, which was helpful when the change in risk was to be evaluated in step 6, especially when assessing the overall change in risk. For instance, if the amount of positive and negative effects were equal for a particular hazardous event, the potentials were helpful insights in concluding if the overall change was negative or positive. If the positive effects addressed only minor risk issues in the conventional sea cage, whereas the negative effects contributed to a significant increase from the risk baseline, the overall risk change was inevitably negative. Expressing the risk reduction potential may also be helpful when future modifications are to be proposed, as this can prevent that previous changes that significantly decreased the risk are not directly or indirectly affected.

- **Conservative assessments**
  The risk impacts of key differences are determined based on conservative assessments. For instance, in the analysis of d=3, the severity of occupational accidents might be limited to minor injuries or short term hospital treatments. However, fatalities can potentially happen when the event (harsh weather hits an on-demand operation) occurs, which was assessed to likelihood L_i=3. In other words, in such cases, the worst-case scenarios are used. Further, if a key difference had a negative effect and there was doubt regarding frequency classes, the highest among the two relevant frequencies was chosen.

- **Multiple consequences**
  In some cases, a negative effect led to an event with several consequences. Analysis of d=13 is an example of this, where improper elevating of the bottom weight ring may result in less structural damage (not a complete break). The frequency of this consequence might be higher compared to a complete break. In other words, the analysis has a weakness as it does not take into account that an event might have different consequences, where these consequences have their own frequencies. If a hazardous event E_i is listed multiple times for the same column, it means that the effect had two effects upon E_i (see for instance analysis of d=11.) The limitation of not providing an overview of consequences is preciously discussed in Section 7.1, and integration of additional

columns to the worksheet may make it easier to include more than one consequence. Nevertheless, since the effects are assessed conservatively, the result includes the worst-case outcome in such cases.

Section 6.5 address uncertainty for each hazardous event and the corresponding change in risk. This paragraph will shortly discuss the uncertainty related to the overall values or risk dimensions. The change in risk to the values of *personnel*, *material*, and *environment* is through discussion in Section 6.5 found to involve a fairly low degree of uncertainty. However, the value of *fish* and the corresponding change in risk is to some degree uncertain. In Norwegian fish farming, there are several more bacterial- and viral diseases and parasites besides the already mentioned PD, AGD, and sea lice. The author has, as previously mentioned, limited knowledge in the discipline of veterinary research and biology, and there might be more diseases or parasites that the key differences will influence. An outbreak of AGD was found to have reduced likelihood due to reduced biofouling, and PD was used as an example of how certain diseases might result in increased severity due to reduced monitoring capabilities. Apart from these impacts, no other key differences were found to affect disease outbreaks. But, due to limited knowledge, there might be unrevealed effects, and the result in terms of fish welfare is considered to involve some uncertainty. In the context of fish welfare, the aspect of diseases is the one considered to involve the most uncertainty, as other judgements on compromised welfare and growth are based on farming experience, OWIs and scientific research, such as the adverse effects documented by Warren-Myers et al. (2022). Overall, change in risk to fish welfare is nevertheless the result that, compared to the others values, has the highest degree of uncertainty.

The result of this thesis could, to some degree, be generalized toward other submersible sea cage concepts. The Atlantis sea cage by Atlantis Subsea Farming AS and the Havliljen/havplattform by Nekst AS (Directorate of Fisheries, 2021d) are probably the submersible concepts in Norwegian aquaculture that are most alike the Midgard Subsea system, and the result of this thesis could, to some extent, be applicable for these concepts. The main difference between Midgard subsea system and the abovementioned concepts is that the whole sea cage, including the floating collar, is submerged. The key differences of operation in the submerged state, center-positioned air dome, net ceiling and related hazards and resulting risk impacts could at some points be valid for these concepts. The technical and operational details of these systems are unknown to the author, and if the results of this thesis are to be used as a reference for the risk picture, a system comparison must be carried out before any conclusion of similarities in risk can be taken. For other submersible concepts intended for offshore farming or where the sea cage design completely differs from a conventional sea cage, it is not recommended to use the result of this thesis as a basis for comparison or reference to changed risk. Overall, the analysis result is based on ScaleAQ's specific system configuration of main components and auxiliary equipment, and as previously discussed, changes in the system description will influence the result. Therefore, as the result is sensitive to deviations in the system description, referrals must be done with care.

8 Conclusion

The technical and operational modifications intended for the Midgard system have undoubtedly influenced the risk picture associated with conventional fish farming, both positively and negatively. Knowledge on what defines risk in conventional fish farming was acquired through the literature study, which alongside a detailed description of the conventional sea cage, was crucial in identifying differences and their effect on risk. A total of 40 differences were identified, of which 30 had an effect and were assigned key differences.

From a holistic perspective, the risk to personnel and environment is the values that, with a fairly low degree of uncertainty, will have reduced risk by implementing the new system. Less equipment and activity on the sea cage, both in terms of normal operation and on-demand operations, have enhanced occupational safety and decreased the risk of pollution. As expected, submergence had a positive effect on the wild stock in terms of lice spread. However, the risk of wild stock interactions through fish escape was not reduced to the same degree. Eighteen effects on the risk to fish escape were identified, and although ten were positive, three uniquely new escape events were identified and foremost attention must be given to these single risk impacts to ensure positive development.

In terms of risk to material assets, in-depth sheltering of auxiliary equipment was a main contributor to reducing the risk of structural damage. At the same time, a new location led to an increased risk of sea cage breakdown, mainly due to an increased threat of heavier shipping traffic and decreased operability of daily technical inspections. Regarding fish welfare, apart from internal sea lice spread, the risk seems to have an overall negative development. The Midgard subsea system had some positive effects, such as reduced handling in normal and on-demand operations. However, considering all four hazardous events connected to fish welfare, 25 negative effects were identified, where sub-optimal environmental conditions and significantly reduced monitoring capabilities of welfare and feeding were central causes for increasing the risk to fish welfare.

The assessments and presentations on overall risk movement are acceptable for gaining an early impression. However, as emphasized several times in the paper, the single key difference and corresponding risk impacts should have the primary attention. Determine risk impact of identified differences was the thesis's main objective, and there are many more effects besides those highlighted in this section. Additionally, the thesis includes risk reduction measures proposed for risk impacts with an ALARP level or higher. Overall, the thesis work is found to be a good decision basis, providing future decision-makers with answers on how planned modifications will change the risk picture, potential measures, and discussion on uncertainty which reflects the reliability of the results. Hopefully, this will be good decision support to whether the intended changes can be preserved, re-designed, or other decisions. Other decisions may be implementing risk reduction measures, doing a more detailed analysis of highlighted issues, accepting the risk through ALARP, or similar.

8.1 Recommendations for further work

For further work, one could adapt the main worksheet (Table 2) to include additional columns for hazards, causes, and consequences. Space for the description of positive and negative effects must nevertheless be included, and integration of such columns must be done in a way that does not compromise readability or user-friendliness. In the thesis, both descriptions of effect and risk determination were done in the same column. The worksheet revision may also look at the possibility of integrating current risk, as this usually will be available/known to the study team (Knowledge of risk baseline is a prerequisite). A simple measure of current risk level in the worksheet will then highlight the key difference's risk reducing or increasing potential. The last proposed worksheet (Table 3) can be adapted to mark if the proposed measures reduce likelihood and/or consequence, or alternatively, being a proactive or reactive barrier. Another further work recommendation is to perform a cost-benefit assessment of the proposed risk reduction measures. The assessment will enhance decision support and be helpful if the risk is to be accepted by the principle of ALARP. Lastly, as the author's knowledge is limited in terms of biology and veterinary research, the result related to fish welfare should be validated.

Bibliography

Akvagroup (n.d.). *Rotorspredere*. URL: https://www.akvagroup.com/sj%C3%B8basert-oppdrett/f-ringsanlegg/rotorspredere.

AQS (n.d.). *Illustration of bath treatment*. URL: https://www.kyst.no/article/investerer-30-millioner-i-nytt-tilbud-om-avlusing/.

AS, Rostein (n.d.). *Transport tjenester*. URL: https://www.rostein.no/tjenester/.

Bannister, Jana et al. (2019). 'Biofouling in marine aquaculture: a review of recent research and developments'. In: *Biofouling* 35.6, pp. 631–648. URL: https://doi.org/10.1080/08927014.2019.1640214.

Bloecher, Nina et al. (July 2018). 'Effects of cnidarian biofouling on salmon gill health and development of amoebic gill disease'. In: *PLOS ONE* 13, e0199842. DOI: 10.1371/journal.pone.0199842.

Coates, Andrew et al. (2020). 'Parasites under pressure: salmon lice have the capacity to adapt to depth-based preventions in aquaculture'. In: *International Journal for Parasitology* 50.10. Special issue on 'Fish Parasitology', pp. 865–872. ISSN: 0020-7519. DOI: https://doi.org/10.1016/j.ijpara.2020.05.009. URL: https://www.sciencedirect.com/science/article/pii/S0020751920301636.

Delfosse, Cyril et al. (Oct. 2016). 'Stress of Atlantic salmon (Salmo salar) in industrial production: a review of causes, consequences and assessment'. In.

Dempster, Tim et al. (2008). 'Behaviour and growth of Atlantic salmon (Salmo salar L.) subjected to short-term submergence in commercial scale sea-cages'. In: *Aquaculture* 276.1, pp. 103–111. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2008.01.018. URL: https://www.sciencedirect.com/science/article/pii/S0044848608000331.

Dempster, Tim et al. (2009). 'Submergence of Atlantic salmon (Salmo salar L.) in commercial scale sea-cages: A potential short-term solution to poor surface conditions'. In: *Aquaculture* 288.3, pp. 254–263. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2008.12.003. URL: https://www.sciencedirect.com/science/article/pii/S0044848608009241.

Directorate of Fisheries (2020). *Nøkkeltall fra norsk havbruksnæring*. Report.

— (2021a). *Cleanerfish (Lumpfish and Wrasse)*. URL: https://www.fiskeridir.no/English/Aquaculture/Statistics/Cleanerfish-Lumpfish-and-Wrasse.

— (2021b). *Forholdet mellom NS 9415 og NYTEK*. URL: https://www.standard.no/Global/PDF/Standard%20Morgen/2021NS9415/3%20Forhold%20mellom%20standard%20og%20forskrift_Fdir200921.pdf.

— (2021c). *Kapasitetsjustering / trafikklyssystemet 2021*. URL: https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Kapasitetsjustering-trafikklyssystemet.

— (2021d). *Oversikt over søknader om utviklingstillatelser*. URL: https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser/Status-ja-nei-antall-og-biomasse.

— (2022a). *Akvakulturstatistikk: matfiskproduksjon av laks, regnbueørret og ørret*. URL: https://www.fiskeridir.no/Akvakultur/Tall-og-analyse/Akvakulturstatistikk-tidsserier/Laks-regnbueoerret-og-oerret/Matfiskproduksjon.

— (n.d.). *Akvakultur, Aktuelle tema*. URL: https://www.fiskeridir.no/Akvakultur.

— (2022b). *Utviklingstillatelser*. URL: https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser (visited on 15th Mar. 2022).

DNV, Det Norske Veritas (2021). *Marine Aquaculture Forecast - Ocean Future to 2050*. Report.

Dürr, Simone and Douglas I. Watson (2009). 'Biofouling and Antifouling in Aquaculture'. In: *Biofouling*. John Wiley & Sons, Ltd. Chap. 19, pp. 267–287. ISBN: 9781444315462. DOI: https://doi.org/10.1002/9781444315462.ch19. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781444315462.ch19. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781444315462.ch19.

E24 (2016). *Ny byggekontrakt til oppdrett*. URL: https://e24.no/karriere-og-ledelse/i/RRdE0A/ny-byggekontrakt-til-oppdrett (visited on 2016).

EFSA, European Food Safety Authority (2018). *Scientific Opinion on the risk for public health related to the presence of mercury and methylmercury in food*. Parma, Italy. DOI: https://doi.org/10.2903/j.efsa.2012.2985.

Egersund Net (2020). *User manual Net bag*. Revision 7.

Espmark, Åsa M. et al. (2019). *Welfare in cleaner fish – operational welfare indicators (OWI) - RENSVEL*. Nofima AS. ISBN: 978-82-8296-589-7.

FAO, Food and Agriculture Organization (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in action*. Rome. DOI: https://doi.org/10.4060/ca9229en.

— (n.d.[a]). *Fisherman's workbook*. URL: https://www.fao.org/3/ah827e/AH827E03.htm.

FAO, Food and Agriculture Organization (n.d.[b]). *The State of World Fisheries and Aquaculture 2020*. URL: https://www.fao.org/state-of-fisheries-aquaculture.

Føre, Heidi Moe and Trine Thorvaldsen (2017). *Årsaker til rømming av oppdrettslaks og ørret i perioden 2010-2016*. Report by SINTEF Ocean AS.

Forrest, Barrie et al. (Jan. 2007). 'Review of the Ecological Effects of Marine Finfish Aquaculture: Final Report'. In: *Cawthron Report* 1285.

Furevik, Dag M. et al. (1993). 'Surface activity of Atlantic salmon (Salmo salar L.) in net pens'. In: *Aquaculture* 110.2, pp. 119–128. ISSN: 0044-8486. DOI: https://doi.org/10.1016/0044-8486(93)90266-2. URL: https://www.sciencedirect.com/science/article/pii/0044848693902662.

Guachamin Acero, Wilson et al. (2016). 'Methodology for assessment of the operational limits and operability of marine operations'. In: *Ocean Engineering* 125, pp. 308–327. ISSN: 0029-8018. DOI: https://doi.org/10.1016/j.oceaneng.2016.08.015. URL: https://www.sciencedirect.com/science/article/pii/S0029801816303419.

Guragain, Prashanna et al. (2021). 'Principles and Methods of Counteracting Harmful Salmon–Arthropod Interactions in Salmon Farming: Addressing Possibilities, Limitations, and Future Options'. In: *Frontiers in Marine Science* 8, p. 965. ISSN: 2296-7745. DOI: 10.3389/fmars.2021.701793. URL: https://www.frontiersin.org/article/10.3389/fmars.2021.701793.

Hallingplast (n.d.). *Fiskeoppdrett*. URL: https://www.hallingplast.no/markeder/fiskeoppdrett.

Hatlem, Odd Helge and Bettina Wickman Kvamme (2016). *Design for Operational Efficiency and HSE in Marine Operations between Floating Cage Collars and Service Vessels in the Aquaculture Industry*. Master theses at NTNU.

He, P. et al. (2021). *Classification and illustrated definition of fishing gears*. FAO Fisheries and Aquaculture Technical Paper No. 672.

Hognes, Erik Skontorp and Christofer Skaar (2017). *Avfallshåndtering fra sjøbasert havbruk*. Report by SINTEF Ocean AS.

Holen, Siri, Ingrid B. Utne and Xue Yang (June 2018). 'Risk dimensions of fish farming operations and conflicting objectives'. In: pp. 1425–1432. ISBN: 9781351174664. DOI: 10.1201/9781351174664-180.

Holen, Siri Mariane (2019). *Safety in Norwegian Fish Farming - Concepts and Methods for Improvement*. Doctoral theses at NTNU, 2019:75.

Holen, Siri Mariane et al. (2018a). 'Occupational safety in aquaculture – Part 1: Injuries in Norway'. In: *Marine Policy* 96, pp. 184–192. ISSN: 0308-597X. DOI: https://doi.org/10.1016/j.marpol.2017.08.009. URL: https://www.sciencedirect.com/science/article/pii/S0308597X16303906.

— (2018b). 'Occupational safety in aquaculture – Part 2: Fatalities in Norway 1982–2015'. In: *Marine Policy* 96, pp. 193–199. ISSN: 0308-597X. DOI: https://doi.org/10.1016/j.marpol.2017.08.005. URL: https://www.sciencedirect.com/science/article/pii/S0308597X16303918.

Holmen, Ingunn et al. (June 2017). 'The status of risk assessments in Norwegian fish farming'. In: pp. 1457–65. ISBN: 978-1-138-62937-0. DOI: 10.1201/9781315210469-183.

Holmen, Ingunn M. (2022). *Safety in Exposed Aquaculture Operations*. Doctoral theses at NTNU, 2022:73.

Holmen, Ingunn M., Ingrid Bouwer Utne and Stein Haugen (2018). 'Risk assessments in the Norwegian aquaculture industry: Status and improved practice'. In: *Aquacultural Engineering* 83, pp. 65–75. ISSN: 0144-8609. DOI: https://doi.org/10.1016/j.aquaeng.2018.09.002. URL: https://www.sciencedirect.com/science/article/pii/S0144860918300712.

Holmen, Ingunn M., Ingrid B. Utne and Stein Haugen (2021). 'Identification of safety indicators in aquaculture operations based on fish escape report data'. In: *Aquaculture* 544, p. 737143. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2021.737143. URL: https://www.sciencedirect.com/science/article/pii/S0044848621008061.

Hvas, Malthe, Ole Folkedal and Frode Oppedal (2019). 'Are salmon and cleaner fish able to thrive in fast water currents? - fish welfare and limits'. In: *Institute of Marine Research (IMR)*. ISSN: 1893-4536. URL: https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2019-37.

Hvas, Malthe and Frode Oppedal (2019). 'Physiological responses of farmed Atlantic salmon and two cohabitant species of cleaner fish to progressive hypoxia'. In: *Aquaculture* 512, p. 734353. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2019.734353. URL: https://www.sciencedirect.com/science/article/pii/S0044848619313845.

Hvas, Malthe et al. (2022). 'Full compensatory growth before harvest and no impact on fish welfare in Atlantic salmon after an 8-week fasting period'. In: *Aquaculture* 546, p. 737415. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2021.737415. URL: https://www.sciencedirect.com/science/article/pii/S0044848621010784.

iLaks (2014). *Marine Harvest hadde tre «LiftUp»-episoder på to uker*. URL: https://ilaks.no/marine-harvest-hadde-tre-liftup-episoder-pa-to-uker/.
IMR, Institute of Marine Research (2011). *Risk assessment – environmental impacts of Norwegian aquaculture*. Report. URL: https://scholar.google.com/scholar_lookup?title=Risk%20Assessment%20%E2%80%93%20Environmental%20Impacts%20of%20Norwegian%20Aquaculture&author=IMR&publication_year=2015.
— (2020). *Oppdrettslaks klarer seg fint uten fôr i opptil fire uker*. URL: https://www.hi.no/hi/nyheter/2020/november/oppdrettslaks-klarer-seg-fint-uten-for-i-opptil-fire-uker.
— (2021a). *Leppefisk*. URL: https://www.hi.no/hi/temasider/arter/leppefisk.
— (2021b). *Risikorapport norsk fiskeoppdrett 2021 - kunnskapsstatus*. URL: https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2021-7.
— (2021c). *Risikorapport norsk fiskeoppdrett 2021 - risikovurdering*. URL: https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2021-8#sec-5.
Johansen, L.-H. et al. (2011). 'Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway'. In: *Aquaculture* 315.3, pp. 167–186. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2011.02.014. URL: https://www.sciencedirect.com/science/article/pii/S0044848611001347.
Korsøen, Øyvind J. et al. (2009). 'Long-term culture of Atlantic salmon (Salmo salar L.) in submerged cages during winter affects behaviour, growth and condition'. In: *Aquaculture* 296.3, pp. 373–381. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2009.08.036. URL: https://www.sciencedirect.com/science/article/pii/S0044848609007479.
Korsøen, Øyvind J. et al. (2012). 'Individual variation in swimming depth and growth in Atlantic salmon (Salmo salar L.) subjected to submergence in sea-cages'. In: *Aquaculture* 334-337, pp. 142–151. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2011.12.031. URL: https://www.sciencedirect.com/science/article/pii/S0044848611010131.
Kyst (2013). *Ta vare på rensefisken gjennom vinteren*. URL: https://www.kyst.no/article/ta-vare-p-aring-rensefisken-gjennom-vinteren/.
Lader, Pål (2020). *Lecture notes BI2065 Aquaculture - Sea cage aquaculture systems*.
Laksefakta (2021). *Spiser laksen bearbeidet animalsk protein?* URL: https://laksefakta.no/hva-spiser-laksen/spiser-laksen-bearbeidet-animalsk-protein-pap/.
Lekang, Odd-Ivar (2020). *Aquaculture Engineering 3^{rd}*. John Wiley & Sons, Ltd.
Leveson, Nancy G. (2011). 'Applying systems thinking to analyze and learn from events'. In: *Safety Science* 49.1. The gift of failure: New approaches to analyzing and learning from events and near-misses - Honoring the contributions of Bernhard Wilpert, pp. 55–64. ISSN: 0925-7535. DOI: https://doi.org/10.1016/j.ssci.2009.12.021. URL: https://www.sciencedirect.com/science/article/pii/S0925753510000068.
Ljungfeldt, Lina Eva Robin et al. (2017). 'A pedigree-based experiment reveals variation in salinity and thermal tolerance in the salmon louse, Lepeophtheirus salmonis'. In: *Evolutionary Applications* 10.10, pp. 1007–1019. DOI: https://doi.org/10.1111/eva.12505. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/eva.12505.
Ministry of Trade, Industry and Fisheries (2011). *Forskrift om krav til teknisk standard for flytende akvakulturanlegg (NYTEK-forskriften)*. URL: https://lovdata.no/dokument/SF/forskrift/2011-08-16-849.
— (2021). *Et hav av muligheter – regjeringens havbruksstrategi*. Report.
Ministry of Trade, Industry and Fisheries (2016a). *Forskrift om bekjempelse av lakselus i akvakulturanlegg*. URL: https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140.
— (2016b). *Forskrift om bekjempelse av lakselus i akvakulturanlegg. FOR-2012-12-05-1140*. URL: https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140.
— (2021). *Forskrift om drift av akvakulturanlegg (akvakulturdriftsforskriften)*. URL: https://lovdata.no/dokument/SF/forskrift/2008-06-17-822.
Moen Marin (2020). *Rensefisk på agendaen*. URL: https://www.moenmarin.no/rensefisk-pa-agendaen/.
Mørenot (n.d.). *Brukerhåndbok taknett*. URL: https://www.morenot.no/aquaculture/brukerhandboker/taknett/.
MOWI (2015). *Salmon Farming Industry Handbook*.
Nesje, Jørgen (2021). 'A preliminary study for risk comparison of two sea-cage designs.' In: *TMR4560 - Project thesis*.
Noble, Chris et al. (2018). *Welfare Indicators for farmed Atlantic Salmon: tools for assessing fish welfare*. Nofima AS. ISBN: 978-82-8296-556-9.

Norwegian Food Safety Authority (2019). *Nasjonal tilsynskampanje 2018/2019 - Velferd hos rensefisk.* URL: https://www.mattilsynet.no/fisk_og_akvakultur/akvakultur/rensefisk/mattilsynet_sluttrapport_rensefiskkampanje_2018__2019.37769/binary/Mattilsynet%20sluttrapport%20rensefiskkampanje%202018%20-%202019.

— (2020). *Veileder for søknader om nye metoder for telling og rapportering av lakselus.* URL: https://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/fiske_og_skjellsykdommer/lakselus/veileder_for_soknader_om_nye_metoder_for_telling_og_rapportering_av_lakselus.38783.

Norwegian Industries, The Federation of (2017). *Roadmap for the aquaculture industry - Sustainable growth.* Report. URL: https://www.norskindustri.no/siteassets/dokumenter/rapporter-og-brosjyrer/veikart-havbruksnaringen_f41_web.pdf.

Nøstbakken, Ole Jakob et al. (2015). 'Contaminant levels in Norwegian farmed Atlantic salmon (Salmo salar) in the 13-year period from 1999 to 2011'. In: *Environment International* 74, pp. 274–280. ISSN: 0160-4120. DOI: https://doi.org/10.1016/j.envint.2014.10.008. URL: https://www.sciencedirect.com/science/article/pii/S016041201400302X.

NRS, Norway Royal Salmon (2019). *Arctic Offshore Farming.* URL: https://www.arcticoffshorefarming.no/home.

NVI, Norwegian Veterinary Institute (2018). *Smitte mellom oppdrettsfisk og villfisk: Kunnskapsstatus og risikovurdering.* Rapport. URL: https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2018/smitte-mellom-oppdrettsfisk-og-villfisk-kunnskapsstatus-og-risikovurdering.

— (2019). *Fish Health Report.* URL: https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2020/fiskehelserapporten-2019.

— (2022a). *Pancreas Disease (PD).* URL: https://www.vetinst.no/sykdom-og-agens/pankreassykdom-pd (visited on 5th Apr. 2022).

— (2022b). *Salmon lice.* URL: https://www.vetinst.no/sykdom-og-agens/lakselus (visited on 28th Apr. 2022).

Oppedal, Frode et al. (Mar. 2020). 'Atlantic salmon cope in submerged cages when given access to an air dome that enables fish to maintain neutral buoyancy'. In: *Aquaculture* 525, p. 735286. DOI: 10.1016/j.aquaculture.2020.735286.

Overton, Kathy et al. (2019). 'Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review'. In: *Reviews in Aquaculture* 11.4, pp. 1398–1417. DOI: https://doi.org/10.1111/raq.12299. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/raq.12299. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/raq.12299.

PSA, Petroleum Safety Authority Norway (2021). *Trends in risk level in the petroleum activity (RNNP).* Summary report. URL: https://www.ptil.no/contentassets/c4222734927b44f2bf2281446ab3ca1c/summary-report-2020.

Rausand, Marvin (1991). *Risiko Analyse - Veiledning til NS 5814* . Tapir Forlag.

Rausand, Marvin and Stein Haugen (2020). *Risk assessment : theory, methods, and applications. Second edition.* Wiley-Blackwell.

Reitan, Kjell I. (2020). *Lecture notes BI2065 Aquaculture - Environmental interactions of aquaculture.*

Robertsen, Roy et al. (2016). *Regelrett eller rett regel? Håndtering og praktisering av regelverket for havbruksnæringen. [in Norwegian] Investigating the Norwegian aquaculture administration.*

SalMar (2021). *Utfyllende informasjon til Mattilsynet i anledning søknad om klarering av lokalitet for Smart Fish Farm pilotprosjekt i Norskehavet.*

ScaleAQ (2014). *Brukerhåndbok - Aqualine FrøyaRing Bunnringssystem.* Granted permission. URL: https://docplayer.me/17984141-Brukerhandbok-aqualine-froyaring-bunnringssystem-rev-30-09-14-a.html.

— (2017). *ScaleAQ Subsea System.* URL: https://www.fhf.no/media/3515/10_-_aqualine_-_midgard_subsea_system_fhf_07022017_i.pdf.

— (n.d.[a]). *LED Light System.* URL: https://scaleaq.no/produkt/led-light-system/.

— (n.d.[b]). *Orbit HD.* URL: https://scaleaq.no/produkt/orbit-hd/?cn-reloaded=1.

Singh, Gerald G. et al. (2018). 'A rapid assessment of co-benefits and trade-offs among Sustainable Development Goals'. In: *Marine Policy* 93, pp. 223–231. ISSN: 0308-597X. DOI: https://doi.org/10.1016/j.marpol.2017.05.030. URL: https://www.sciencedirect.com/science/article/pii/S0308597X17302026.

SINTEF (2021). *Lecture notes TMR4137 - Sustainable Utilization of Marine Resources.*

Skretting (2022). *Hvor mye fôr trengs for å vokse frem en fisk?* URL: https://www.skretting.com/no/aapenhet-og-tillit/ofte-stilte-spoersmaal/hvor-mye-for-trengs-for-aa-vokse-frem-en-fisk/ (visited on 8th Feb. 2022).

SNL, Store Norske Leksikon (2022). *Rensefisk*. URL: https://snl.no/rensefisk.

Standard Norge (2021). *NS9415*. Flytende akvakulturanlegg — Lokalitetsundersøkelse, prosjektering, utførelse og bruk. URL: https://www.standard.no/nettbutikk/sokeresultater/?search=ns9415&subscr=1.

Stien, Lars H., Frode Oppedal and Tore Kristiansen (2016). 'Dødelighetsstatistikk for lakseproduksjon'. In: *Risikorapport norsk fiskeoppdrett 2016. Havforskningsinstituttet.*

Stien, Lars H. et al. (2021). 'Dyrevelferd i norsk fiskeoppdrett'. In: *Risikorapport norsk fiskeoppdrett 2021 - kunnskapsstatus. Havforskningsinstituttet.*

Stradmeyer, Lee, Neil B. Metcalfe and John E. Thorpe (1988). 'Effect of food pellet shape and texture on the feeding response of juvenile Atlantic salmon'. In: *Aquaculture* 73.1, pp. 217–228. ISSN: 0044-8486. DOI: https://doi.org/10.1016/0044-8486(88)90056-7. URL: https://www.sciencedirect.com/science/article/pii/0044848688900567.

The Federation of Norwegian Industries (2017). *Roadmap for the aquaculture industry - Sustainable growth*. Report. URL: https://www.norskindustri.no/siteassets/dokumenter/rapporter-og-brosjyrer/veikart-havbruksnaringen_f41_web.pdf.

The Norwegian Government (2018). *Havbruk til havs*. Report. URL: https://www.regjeringen.no/no/dokumenter/havbruk-til-havs/id2625352/.

TU (2021). *John Fredriksens Mowi får 5,8 millioner i klimastøtte*. URL: https://www.tu.no/artikler/john-fredriksens-mowi-far-5-8-millioner-i-klimastotte-br/513543.

Uglem, Ingebrigt, Johanna Järnegren and Nina Bloecher (2020). *Effekter av organiskt utslipp fra havbruk i Norge*. NINA - Norsk institutt for naturforskning. URL: https://www.sintef.no/globalassets/sintef-ocean/arrangement/slam/leveranse-l2.1-effekter-av-organisk-utslipp-fra-havbruk-nina.pdf.

United Nations (2021). *Global Population Growth and Sustainable Development*. Department of Economic and Social Affairs, Population Division. URL: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2022_global_population_growth.pdf.

— (2022a). *Goal 2: Zero hunger*. URL: https://www.un.org/sustainabledevelopment/hunger/ (visited on 15th Mar. 2022).

— (2022b). *The 17 Sustainable Development Goals (SDGs)*. URL: https://sdgs.un.org/goals (visited on 10th Feb. 2022).

USGLC, U.S. Global Leadership Coalition (2022). *COVID-19 Brief: Impact on Food Security*. URL: https://www.usglc.org/coronavirus/global-hunger/.

Utne, Ingrid et al. (June 2017). 'Risk Management in Aquaculture: Integrating Sustainability Perspectives'. In: V07BT06A054. DOI: 10.1115/OMAE2017-61845.

Vinnem, Jan-Erik and Willy Røed (2020). *Offshore Risk Assessment Vol. 2 - Principles, Modelling and Applications of QRA Studies, Fourth Edition*. Springer.

Waagbø, Rune et al. (Mar. 2017). 'Short-term starvation at low temperature prior to harvest does not impact the health and acute stress response of adult Atlantic salmon'. In: DOI: 10.7287/peerj.preprints.2837.

Wang, Xinxin et al. (Aug. 2012). 'Discharge of nutrient wastes from salmon farms: Environmental effects, and potential for integrated multi-trophic aquaculture'. In: *Aquaculture Environment Interactions* 2, pp. 267–283. DOI: 10.3354/aei00044.

Warren-Myers, Fletcher et al. (2022). 'Full production cycle, commercial scale culture of salmon in submerged sea-cages with air domes reduces lice infestation, but creates production and welfare challenges'. In: *Aquaculture* 548, p. 737570. ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2021.737570. URL: https://www.sciencedirect.com/science/article/pii/S0044848621012333.

WFP, World Food Programme (2022). *Unprecedented needs threaten a hunger catastrophe*. URL: https://docs.wfp.org/api/documents/WFP-0000138231/download/.

World Food Programme (2022). *Projected increase in acute food insecurity due to war in Ukraine*. Report.

Yang, Xue, Ingrid B. Utne and Ingunn M. Holmen (2020). 'Methodology for hazard identification in aquaculture operations (MHIAO)'. In: *Safety Science* 121, pp. 430–450. ISSN: 0925-7535. DOI: https://doi.org/10.1016/j.ssci.2019.09.021. URL: https://www.sciencedirect.com/science/article/pii/S0925753518319003.

Appendix

A Risk impact of key differences

The worksheet begins at the following page.

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**
1	External interface change						The power cables (EI4) and the feeding pipe (EI3) still float and enter the system boundary at the water surface. Due to an increased threat (d=5) of storms and large waves, the likelihood of a broken feeding pipe or power cable has increased. In the winter season, harsh weather periods might result in several weeks without feeding as repair operations will involve too high a risk for personnel. During repair, the net bag must be elevated, increasing the likelihood of lice infestation. Long periods (1-2 months) without feed will not impact fish welfare according to Hvas et al. (2022). The study also shows negative SGR (reduced body mass) during the 8-week fasting period and thus an extreme deviation from the expected growth rate. Following refeeding, the study recorded great compensatory growth and that the fasted fish were able to catch up control group's weight after three months. However, such a severe deviation in growth is unfavorable and could delay production, depending on the time of occurrence and season. If the fish has a low condition factor, i.e., low fat levels, longer periods without feed may impact immunity and thus increase susceptibility to diseases (Waagbø et al., 2017). It is expected that a fish farm will experience such an event (winter storms, broken feed pipe) at least once in a decade.	6 7 9	4 4 4	2 3 5	E_6 - Structural damage E_{10} - Sea lice or disease spread E_{11} - Loss of growth
2	More remote	Farming further from shore/fjords enables more space between sites and less proximity to migrating wild salmon. Conventional sea cages in fjords have restricted site availability					A more remote site might experience an increased emergency response time. The majority of serious accidents occur during operations at the cage (S. M. Holen et al., 2018b).				

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**$RPN_{i,d}$**	**$L_{i,d}$**	**$S_{i,d}$**	**Hazardous event (E_i/E_i^*)**	**Justification**	**$RPN_{i,d}$**	**$L_{i,d}$**	**$S_{i,d}$**	**Hazardous event (E_i/E_i^*)**
2	Continued.	due to high sea lice pressures, and a more remote location will most likely have positive effects in terms of reduced frequency of lice infestations, both internally and at wild stock. However, it is not a movement offshore, and the likelihood of infestation is still assessed as occasional. Reduced lice pressure in the remote area decreases the severity. The severity reduction towards wild stock is considered higher as moving out of narrow fjords gives more space to farming sites for migrating wild salmon.	6 7	4 4	2 3	E_5 - Sea lice and disease spread - wild stock E_{10} - Sea lice and disease spread	The occurrence frequency of such accidents will most likely be reduced as there will be less activity on the cage (both normal operation and on-demand). However, the severity might be larger when accidents occur due to increased response time from external emergency forces.	7	3	4	E_1 - Occupational accidents
3	Environmental condition	The new environmental condition for the sea cage will enhance fish welfare in terms of no exposure to wave activity, as well as the fish will experience more even current conditions due to the elimination of fluctuating wind-generated currents. Negative surface events in conventional sea cages frequently occur (L_i=5) and compromise fish welfare to some degree (S_i=1). Structural risk due to environmental loads is not considered, as this is to be accounted for in detailed engineering.	0	0	1	E_8 -Compromised welfare	It is assumed that the farmers will carry out on-demand operations under the same weather restrictions as before. The working platform (floating collar and vessels) and on-demand operations are still the same, but more exposed areas will bring smaller weather windows. If the operations do not go as planned, stressful situations among the crew might occur, and the risk of accidents increases. If harsh weather hits the operation or must be aborted in a vulnerable state (e.g., during crowding), all the risk dimensions might be seriously affected. The frequency of such an event is assessed to class "possible" (less on-demand operations). In conventional farming, the event is assessed as remote.	7 7 7 5 7 7 8 8	3 3 3 3 3 3 3 3	4 4 4 2 4 4 5 5	E_1 - Occupational accidents E_2 - Man overboard E_3 - Fish escape E_4 - Littering to sea E_6-Structural damage E_7 - Breakdown of sea cage E_8 - Compromised welfare E_9 - Fish death
4 6 7	External threats						The altered external threats of heavier shipping traffic, submarines, and whales mainly pose a threat towards the hazardous events of fish escape and breakdown of sea cage	6 6	2 2	4 4	E_3 - Fish escape E_6 - Breakdown of sea cage

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**
11	Ceiling	The ceiling prevents falling objects from entering and creating holes in the bottom of the net bag. Equal mesh size means objects small enough to bypass the roof will exit in the conical part. Thus, such an event is eliminated for the new cage. L_i=4 and S_i=2 for this event in conventional sea farming.	0	0	2	E_3 - Fish escape	Falling objects landing on the ceiling might create a hole over time or instantly if the impact is high. Due to less equipment and activity on the floating collar, the frequency of falling objects is considered low. Nevertheless, it is expected to happen once in a decade. Since the hole will be present in the ceiling where most of the salmon are located, major escapes may occur. Furthermore, the ceiling system introduces the new hazardous event of *zip not locked properly*. The mechanism and procedure of closing/securing the zipper are under development and unknown to the author. Human error is a main hazard, and an occasional frequency class is chosen. The consequence is assessed as severe since it assumed that the zipper might open gradually with the vertical movements of the net bag (wave activity in the surface) and consequently leading to big escapes. Lastly, the ceiling prevents the salmon from jumping. When present at a conventional sea cage, salmon jumping appears frequently and is expected to be observed. Studies have shown that jumping activity increase with increasing lice infestation (Furevik et al., 1993) or stressors/threats from below which frighten the fish to the surface (Noble et al., 2018). Jumping activity can also be preparation for ascending a river, where the salmon have to jump to pass waterfalls. The new hazardous event of "jumping denied" constantly occurs and compromises fish welfare as the ceiling prevents the salmon from expressing normal surface behavior.	7 8 8	4 4 5	3 4 3	E_1^* - Hole in ceiling E_3 - Fish escape E_2^* - Zip not locked properly E_3 - Fish escape E_3^* - Jumping denied E_8 - Compromised welfare

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**
13	Winch	Single point bottom ring handling with cranes at conventional sea cages is a hazardous operation. In the last two decades, crane/lifting accidents during operations have been one of the main causes of occupational fatalities and injuries in the industry (S. M. Holen et al., 2018b). The technical change of the winch removes the need to use cranes when handling the bottom ring. Accidents during bottom ring handling at a conventional farm are assessed to L_i=4 and S_i=3.	0	0	3	E_1 - Occupational accidents	The winch introduces risk to occupational safety in terms of electric shocks during maintenance/repair. However, both frequency and severity are considered low for such events. By simultaneous lifting of all points, less awareness is paid towards each lifting point compared to when lifting with crane. If one, or worst case several adjacent winches fail (or does not work properly, e.g different speeds), the bottom ring might break as it not stiff enough to carry unsupported points..	5 6	3 3	2 3	E_1 - Occupational accidents E_6 Structural damage
14	Air dome						The submergence of the net bag and the possibility of air dome failure introduce the new hazardous event of *No air access*. Broadly, this event might be caused by the two preceding events of air dome failure or that the fish does not utilize the air dome (Noble et al., 2018). Biological studies of submerged cages with no air access for Atlantic Salmon have shown that short-term and shallow submergence have relatively little effects in terms of fish welfare and growth, where the studies address submergence feasibility for both post-smolt (Korsøen et al., 2012) (Dempster et al., 2009) and larger salmon (1.7kg) (Dempster et al., 2008). The studies' net ceiling depths varied from 3-10m and trial periods of 15-22 days. In parallel with the post-smolt experiment, Korsøen et al. (2012) submerged large salmon (4kg) below 10m for 42 days without air access, where the result showed that the coping ability of long-term submergence varied greatly and many individuals had poor growth rates and fin conditions.	6 6	3 3	3 3	E_4^* - No air access E_{11} - Loss of growth E_8 - Compromised welfare

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14	Continued						Korsøen et al. (2009) support the effect of compromised welfare and reduced growth, where 3.5kg salmon were submerged to depths of 10-24m, and monitoring with echo-sounders indicated almost a complete loss of gas in the swimming bladders after 22 days. The negatively buoyant fish showed abnormal behavior through tail-down/head-up and fast swimming compared to the control fish. Mortality levels were not affected, but the fish had considerable more erosion on fins/snouts and compressed vertebrae in the tail region. Feed utilization and thus growth was also significantly lower. Korsøen et al. (2009) study concludes that Atlantic salmon without air access and submerged to depths below 10m (ceiling) will experience reduced welfare and growth after two weeks. These numbers were found most relevant for this analysis. Potential triggering events of air dome failure might be compressor failure, broken air supply pipe, fastening of air dome loosen/breaks and thus the air dome turns around. The frequency of a two-week absence of air is assessed as possible.				
15	Feeding system	Crushed pellets and dust will be avoided with water transportation of pellets and underwater feeding. Furthermore, the pellets will be softer and can potentially enhance feed intake and growth (Stradmeyer et al., 1988). However, the condition of dry pellets in conventional sea farming is not assessed to have a big impact on growth, and assessed to L_i=5 and S_i=1. Other conditions such as disease could result in severe loss in growth.	0	0	1	E_{11} - Loss of growth					

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16	Camera system						Camera lenses get dirty several times during the production cycle in conventional sea cages. But, as it is easy to wipe off the lenses, it is not considered a hazardous event. However, in the new system, it becomes a hazardous event as the net bag must be elevated to clean the lenses, increasing the risk of lice infestation. Because the cameras are constantly facing upwards and interfering with descending waste, dirty lenses are expected to occur even more frequently in the new system. It would also take some time to access/clean cameras, increasing the severity to S_i=2. For effect on feeding, see analysis of d=30.	7	5	2	E_5^* - Dirty camera lenses E_{10}- Sea lice and disease spread
17	Mortality system	Moving the equipment outside the net bag eliminates the likelihood of wear/tear towards the netting, especially in the bottom where the cone (3.4.1) is placed. The cone is large/heavy and could create large rifts and escapes if alive fish are present in the bottom. Incorrect installation or removal of the cone might also be a central cause of holes in the netting. According to Føre and Thorvaldsen (2017), approximately 120000 fish escaped through holes caused by the cone (8 events). Escape events related to the cone are now eliminated, and considering a conventional fish farm, classes are assessed to L_i=3 and S_i=3.	0	0	3	E_3 - Fish escape	Having the PVC hose outside the net bag can also contribute negatively to fish escape. If a hole in the PVC hose occurs or the fasting to the net bag detaches, a large group of fish might swim through it. Alive fish are usually not present in this area due to restricted space. Still, they might be, and events of "pumping" alive fish during dead fish removal frequently occurs in conventional sea cages. In the new system, the fastening might detach due to fatigue fracture caused by high relative motions between the net bag and the PVC hose. Such motions would occur when the "pumping" of air starts. Further, if a hole in the PVC hose is not discovered and the pumping of dead fish starts, many alive salmon could be released into the environment. The most significant threat to a hole in the PVC hose is probably predators (e.g., seals), which are attracted by dead fish in the hose and might bite a hole to access it. The stationary camera system pointing upwards	7	4	3	E_6^* - Hole in PVC hose E_3 - Fish escape

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17	Continued						also gives less flexibility in controlling the amount of fish present in the bottom (both alive and dead), thus increasing the frequency of pumping alive fish. A hole is expected to occur at least once in a decade.				
18	Cleaner fish components	On a national basis, Hognes and Skaar (2017) assume that 70% of the cages are equipped with four hideouts, each with 35kg of polyethylene. The hideouts are often laid on the collar to get dried/cleaned, which increases the likelihood of losing the hideout (or parts of it) to the sea (e.g., if a storm occurs). This littering event at conventional sea cages is assessed to L$_i$=4 and S$_i$=2.	0	0	2	E$_4$ - Littering to sea					
21	Interface, fastening of aux. eq.	The flexible floating collar often deforms and increases its eccentricity as current forces push on the net bag. In conventional sea cages, if ropes used to fasten auxiliary equipment to the handrail is too short when the collar becomes more elliptic, they might snap or damage the handrail or the equipment itself. This issue concerns all auxiliary equipment inside the net bag, fastened with ropes to the handrail (II.10, II,11, II.13, II.14). In case of snapped ropes, drifting or loose objects inside the cage might create holes in the netting. The main hazard is human error during the installation of the equipment. The likelihood of structural damage is assessed to L$_i$=4 and with severity S$_i$=2. The event of fish escape due to drifting/loose equipment is assessed to be less frequent (L$_i$=3) due to daily inspections. S$_i$=3 as some equipment (e.g. the spreader) can make large rifts in the upper part of the net bag where most salmon are present.	0 0	0 0	2 3	E$_6$ - Structural damage E$_3$ - Fish escape	Human error is also a hazard when fastening the auxiliary equipment with ropes to the load-bearing elements in the net bag. If not appropriately tied, the ropes might loosen, and the loose equipment could create holes. Traditional daily inspections of these fastenings are unfeasible, and it might take some time before loose lights or the sea lice camera are discovered. A loose air dome, spreader, or camera is assumed to be quickly noticed. In other words, escapes caused by wear from loose objects might occur more frequently due to less control of fastenings and could result in larger escapes due to a longer time to notice. Another related escape event could happen if the fastening is mounted to the net instead of the load-bearing elements and the ropes get tension. Lastly, the net bag must be elevated due to repair if some of the aforementioned human errors occur, and thus risk for lice infestation increases.	7 7 7	4 4 4	3 3 3	E$_3$ - Fish escape E$_3$ - Fish escape E$_{10}$ - Sea lice and disease spread

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22	Interface, collar - netting	According to Føre and Thorvaldsen (2017), there were in total seven escape events due to conflicts between the floating collar and the net (2010-2016). Three of them in the category *hole in net* (27 000 fish, 2% of total in category) and four in the category *submerged net* (190 000 fish, 68% of total). Generally, escapes due to nets underwater occur much less frequently compared to holes in the net, but they might result in very large escapes. This is especially true for conflicts with the floating collar, where almost 50 000 fish escaped at each submerged net event. These types of escape events are no longer relevant, and for a conventional fish farm, an overall RPN for escaped fish due to holes or a submerged net caused by conflicts with the floating collar is assessed to RPN=6 ((L_i=3, S_i=3)	0	0	3	E_3 - Fish escape					
23	Interface, expansion system - collar system.	With slack bottom ring suspension lines made out of ropes, there will be no wear and tear on the net bag in situations where these two interacts (e.g., during strong currents). Wear on the net bag from stiff suspension chains is a leading cause of large escape events in conventional sea cages. The suspension line accounted for 26% (approx. 350 000 fish, 11 events) of the salmon escaping through a hole (Føre and Thorvaldsen, 2017)). Considering a conventional fish farm, classes are assessed to L_i=4 and S_i=3 for this eliminated event.	0	0	3	E_3 - Fish escape	A slack bottom ring suspension line might create conflicts with propellers if too slack. Causes for this might be that winch procedures are not followed and lack of attention during maneuvering. The most related hazard is human error. Such an event could lead to structural damage in terms of a broken suspension line, damaged propulsion system, winch, and/or bottom ring.	6	4	2	E_6 - Structural damage
24	Interface, expansion system - net bag	This change enhances the expansion capability of the system and helps the net bag retain a higher volume during strong current conditions (Documented effect by ScaleAQ).	5	4	1	E_8 -Compromised welfare					

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24	Continued	Losing cylindrical shape and compressed net bag volume due to rough current conditions frequently occurs in conventional sea cages (L_i=5) and could, to some degree, impact fish welfare and growth (S_i=1). Bottom ring suspension in the net bag instead of the floating collar will reduce the likelihood of such compressed net bag events.	5	4	1	E_{11} - Loss of growth					
25	Interface, handrail	Removing all these interfaces (ropes) also removes one of the main hazards of littering at conventional sea cages, i.e., equipment on the floating collar. There are almost no ropes at the floating collar in the new system. Human activity at the cage is another hazard to littering, which now occur much less frequently. Additionally, cutting ropes with a knife are the main cause to cut injuries in the industry (S. M. Holen et al., 2018a). The study also shows that handling/pulling ropes with capstans are one of the leading causes to crush injuries (e.g., handling of hideouts). Due to less ropes and handling of associated equipment, the frequency of these accidents will most likely be reduced.	5 5	4 3	1 2	E_4 - Littering to sea E_1 - Occupational accidents					
27	Interface, submerged net-entries						Escape events through net entries are improbable to occur in conventional sea cages due to daily inspections, and as the entry is above the water surface, very few individuals would escape, i.e. low risk. In the new system, more net entries and the fact that they are submerged increase the likelihood of escapes. Further, the feeding pipe entry is positioned in the center of the ceiling, where the majority of the fish are located. Human error during assembly is a main hazard.	7	4	3	E_3 - Fish escape

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28	Normal operation: Submerged as main state	A recent study of farming Atlantic salmon in a submerged cage integrated with an air dome to the ceiling has shown promising results, where groups of 10,000 salmon immersed to 10m depth sustained normal growth rates and behaviour (Oppedal et al., 2020). However, the study had trial periods of 5-7 weeks and emphasized the need for trials that last entire production cycles to validate the feasibility of submerged cages with air domes and their lice-reducing potential. Thus, Warren-Myers et al. (2022) followed up this demand and tested three submerged cages at 15 meters depth, farming 6000 salmon/cage over an entire production cycle (0.2kg at sea transfer - 5kg at harvest). The result showed positive effects on lice infestation rates throughout the production cycle, where the submerged cages, on average, had 55% lower lice numbers compared to the sea surface control cages. At the most, the lice level was 93% lower. The sampling of lice and fish health was carried out by raising the net bag every eight weeks. Continuous delousing with lumpfish was also applied in the experiment. Since the Midgard Subsea cage is to be held at depths of 20-30m and equipped with a lice camera for counting, it's reasonable to assume that the cage will have the same potential, even though there will be no cleaner fish. Thus, high lice pressure during normal operation are expected to occur once in a decade, and consequently, the severity level also gets lower. The frequency of impact on wild fish is assessed even lower as a farm with subsea cages is located more remote.	4 5	3 4	1 1	E$_5$ - Sea lice and disease spread - wild stock E$_{10}$ - Sea lice and disease spread	The already mentioned study (see *positive effects*) by Warren-Myers et al. (2022) also revealed negative effects. Firstly, it is important to mention that the experiment's cage setup and production method are mostly the same as for the Midgard Subsea cage. Therefore, the study is found as a good reference for supporting the assessment of this key difference. It is also the first study of a full production cycle (June 2019 - June 2020) with submerged cages fitted with air domes. Roughly, the experiment cages were equipped with a center-positioned air dome and feeding, bottom weights, lights, environmental sensors, a camera for monitoring behavior, and mortality system for daily collection and registration. But there are some differences, and besides those already mentioned in *positive effects* (submergence depth, elevation for lice counting, lumpfish), the experimental cages also were smaller in dimensions, equipped with an echo sounder, and the camera was positioned under the air dome. When it comes to the result, the submerged cages were not so promising in terms of welfare and growth. At harvest (June 2020), the overall mortality was 2.5 times higher for submerged cages compared to the control cages. The cumulative mortality for the submerged cages increased distinctly during the last four months of the 12-month grow-out period and accounted for almost 70% of the overall mortality. The report links sub-optimal oxygen saturation levels as the main influencing factor to the increased mortality, as the oxygen levels had been similar to the control cages before the increase.	9 8 8	5 5 5	4 3 3	E$_8$ - Compromised welfare E$_9$ -Fish death/ increased mortality E$_{11}$ - Loss of growth

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28	Continued	Another positive effect of the submerged state is the reduced amount of biofouling on the netting. Fouled netting conditions to the degree where it becomes harmful are usually avoided in conventional sea cages by net cleaning (separate analysis, d=38). Still, harmful events might occur, especially in the summer/fall when fouling intensifies and the availability of service vessels is limited. Gradual occlusion of the netting could as previously mentioned lead to hypoxia due to reduced water exchange and oxygen levels in the upper water layers, which compromise welfare and growth. Reduced water exchange also prevents waste removal, and the fouled netting will act as housing for parasites and diseases. And if the fish choose a zooplankton diet due to stress or low food availability, infection and disease outbreak risk increases considerably. AGD is a disease that is associated with several fouling species (Dürr and Watson, 2009). Further, occluded or even blocked mesh openings can potentially increase the drag by three times (Dürr and Watson, 2009), causing more tension to components which could lead to material fatigue. The change to a submerged net bag reduces the frequency of such harmful fouling events (L$_i$=2). Further, the new system eliminates some previous and central fish escape events. According to Føre and Thorvaldsen (2017), conflicts with mooring and vessels represented 8% (5 events) and 7% (10 events) of the total escapes in the category *holes in the netting*. On average, conflicts with mooring and	4 5 5 5	2 2 2 2	2 3 3 3	E$_8$- Compromised welfare E$_{11}$-Loss of growth E$_{10}$ - Sea lice and disease spread E$_6$- Structural damage	Regarding individual-based welfare indicators, the submerged cages generally scored worse on the eye condition and mouth/jaw damage. Control also scored slightly better at skin and fin conditions. Further, growth rates were far better for control fish in certain periods and showed an average SGR that was 30% higher compared to the submerged cages. Differences in temperature between the cages and the reduced level of dissolved oxygen were the main reasons for low growth performance in the submerged environment. The temperature difference was highest in the early production phase (autumn 2019), and the control cages experienced better growth rates in the more optimal/warmer surface water. In the winter, when the coldest water occurs in the surface, the SGR was equal for both cage types. At the trail's end, the submerged cage had almost half the mean harvest weight (2.8kg) compared to the control (5kg). The study also discussed the viability of using air domes. It concluded that domes seem to be a feasible solution in providing the fish with air to refill their swimming bladder. The study used a 2.5 m diameter octagonal dome, and data on echo strengths showed no signs of abnormal swimming bladder fullness throughout the trial, indicating that the fish had utilized the air dome competently. Thus, the study indicates that sub-optimal environmental conditions of lower oxygen saturation and colder water might occur in submerged farming, resulting in considerable growth reduction and compromised welfare. The report also shows that oxygen levels and temperature				

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28	Continued	and vessels had approximately 21400 and 10700 fish per event, respectively. Conflicts in this regard are mainly linked to rifts caused by bridles or propellers. At a conventional fish farm, the associated risk for these two eliminated escapes events is assessed to RPN=7 (L$_i$=4, S$_i$=3). Another eliminated escape event is holes due to drifting objects, but according to the study mentioned above, the average severity is approximately 2000 fish per event. Conflicts with auxiliary equipment due to harsh weather poses a threat to holes in the net, and approximately 80000 fish escaped (10 events) due to conflicts with auxiliary equipment. Such escape events are not directly eliminated (net bag occasionally lifted, more exposed locations), but the frequency is now assessed to L$_i$=3. These negative surface events might also result in structural damage to the auxiliary equipment.	0 0 0 5 5	0 0 0 3 3	3 3 2 2 2	E$_3$ - Fish escape E$_3$ - Fish escape E$_3$ - Fish escape E$_3$ - Fish escape E$_6$ - Structural damage	are even less optimal at depths that are intended for the new system (20-30m). Environmental conditions are site-specific, but values from Warren-Myers et al. (2022) are used to assess conservatively.				
29	Normal operation: Start-feeding						No hand-feeding and proximity to the smolt after sea transfer might increase the risk related to fish welfare and growth. Warren-Myers et al. (2022) did not hand feed the smolt as the sea cages were smaller, and thus the fish were much closer to the descending pellets (O. Folkedal, personal communication, April 28, 2022). The new system has the exact dimensions of a conventional cage, and the same adaption issues related to sea transfer are still relevant. The motivation for hand-feeding is previously explained (Section 4.4.1), and the removal of the operation thus increase the risk of reduced growth in the early production phase and the occurrence of emaciated fish (losers). In conventional sea cages, loser fish are easily spotted	7 7 7	4 4 4	3 3 2	E$_8$ - Compromised welfare E$_9$ - Fish death E$_{11}$ - Loss of growth

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29	Continued						and collected. In the new system, it would be much more demanding to control the occurrence of loser fish. And if any observations are made, it is unlikely that the net bag will be elevated due to lice infestation risk. An increased amount of loser fish and more challenging observation/collection might cause prolonged suffering for hundreds or maybe thousands of fish in this early and vulnerable production phase.				
30	Normal operation: Feeding						Stationary cameras pointing upwards in the bottom of the net bag might reduce the farmers' flexibility in monitoring feed intake and thus make the feeding operation less accurate. As mentioned in Section 4.4.1, uneaten pellets and fish behavior are the main indicators of appetite during feeding. The fixed cameras are suitable for observing uneaten feed and might help monitor the horizontal spread of pellets, which is difficult in the conventional cage if the water current direction is perpendicular to the camera ropeway. However, without the opportunity to follow the feed activity vertically in the water column and with an increased distance to the feeding fish, the farmers have less opportunity to adjust feeding based on fish behavior, especially in case of turbid water or dirty camera lenses. This might cause insufficient saturation. High turbidity could be an indication of the presence of phytoplankton, which can cause sudden changes in oxygen levels (Noble et al., 2018) and makes it even more critical to monitor fish behavior during feeding. The difference in the camera system leading to adverse feeding is assessed to cause a large deviation in growth.	8	5	3	E_{11} - Loss of growth

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31	Normal operation: Sea lice monitoring	Continuous counting with a lice camera will most likely provide the farmers with more reliable lice and a better understanding of the prevalence of lice in the cage. Thus, operating with a lice camera could better support decisions of lice reducing measures and, in this way, mitigate lice spreading before it becomes a major problem. The likelihood of sea lice spread due to misconception of lice levels is therefore reduced to remote. As manual lice counting is not to be carried out, the fish is no longer exposed to the stress they experienced while being caught with the scoop net and anesthetized. In terms of welfare, the event is assessed to RPN=6 (L$_i$=5, S$_i$=1). Elimination of this operation also removes the risk related to crane accidents. The operation is carried out once in a week, and the crane is actively used in this context, as it usually requires rapid and precise crane movement to catch the fish. Occupational accidents during manual lice counting might occur once a decade and are assessed with overall severity of S$_i$=2.	5 0 0	2 0 0	3 2 1	E$_{10}$- Sea lice spread E$_1$- Occupational accidents E$_8$- Compromised welfare	Manual sampling and counting of lice in conventional farming allow farmers to monitor other individual OWIs in addition to sea lice (e.g., examination of fin damage, skin condition, shortened/damaged operculum, jaw damage, and gill status to detect AGD). Since the operation is carried out regularly, the farmers can detect and monitor the development of certain diseases or other welfare issues and further take action at an early stage to mitigate the problem. Now, since the new system is only to be elevated in case of emergency or certain on-demand operations (see d=28), the risk of compromised welfare and disease spread increases. The above-mentioned events are assessed to occur with a likelihood of L$_i$=4 due to less control of fish health and removed practice of individual-based OWIs.	7 7 7	4 4 4	3 3 3	E$_8$- Compromised welfare E$_9$- Fish death E$_{10}$- Disease spread
32	Normal operation: Fish welfare monitoring - OWI usage						Apart from the environmental-based OWIs, the animal-based OWIs (group and individual) have reduced operability. The increased risk with reduced operability of individual-based OWIs in the context of the changed lice counting operation is already assessed (analysis of d=31). However, daily observing the fish from the floating collar is a central part of welfare monitoring in conventional fish farming. This proximity to the fish makes it possible to apply group-based OWIs such as *deviation from normal behavior* and				

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32	Continued						several of the individual-based OWIs when walking around a conventional sea cage. *Daily technical inspection* and *dead fish removal* are daily operations where farmers are present at the floating collar and enable them to monitor fish welfare consistently. Observation of suffering individuals (injuries, wounds, loser fish) and changes in behavior could be early warning signals of potential welfare issues, making frequent cage visits crucial in understanding the fish welfare status and initiating correct measures to ensure the best possible welfare. The new system could still apply many group-based OWIs through the underwater cameras. Still, the fixed camera configuration is less suitable for observing school behavior (as indicated in the analysis of d=30). Mortality and sea lice are most likely the only animal-based OWIs equally viable compared to the conventional system. New OWIs of *Abnormal tilt-angles* and *Increased swimming speed* will also be difficult to apply. In other words, reduced operability for the majority of the animal-based OWIs might result in severe consequences for fish welfare throughout the production cycle. More individuals will probably suffer, as well as stress, signs of certain diseases or other welfare issues will be harder to detect, consequently compromising welfare and potentially increasing mortality. For instance, Pancreas Disease (PD) is a well-known viral disease in Norwegian Aquaculture which could be detected by signs of a sudden drop in appetite and/or change in behavior when sick fish cluster towards the current direction in the	8 8 8	4 4 4	4 4 4	E$_8$ - Compromised welfare E$_9$ - Fish death/ increased mortality E$_{10}$ - Disease spread

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**
32	Continued						water surface (Noble et al., 2018). PD infected fish will start to die after 2-3 weeks (NVI, 2022a) and can cause high and long-lasting mortality (1-32 weeks) (Noble et al., 2018). Early detection makes it possible to plan for slaughter which mitigates suffering and mortality in the case of PD. Early discovery can also restrain severity by minimizing stress, as stress among infected fish can trigger and escalate a PD outbreak. Conclusively, occurrence of prolonged mortality or suffering among the population is assessed to occur at least once a decade due to considerably reduced control of fish welfare.				
34	Normal operation: Cleaner fish	Operating without cleaner fish enables a larger mesh size throughout the production. Mesh size is limited by smolt size and cleaner fish. Thus, the new system could have a larger mesh size, customized by the smolt size. A larger mesh size results in a lower solidity ratio and allows for increased water exchange in the cage. The water exchange rate depends on current speed and is important for water quality (oxygen, waste removal). Low current speed might lead to hypoxia, and factors such as net mesh, biofouling, and fish biomass influence the rate of exchanged water in the cage (Noble et al., 2018). Since a larger mesh size will also experience less occluded mesh openings during fouling, a higher water exchange rate would be experienced in the new system compared to conventional, and hypoxia events could be avoided in case of low current speeds. The likelihood of compromised welfare in terms of poor water quality and hypoxia due to the mesh structure is now assessed as possible.	5	3	2	E$_8$- Compromised welfare					

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**
35	Normal operation: Daily inspection						The negative effects of reduced control of auxiliary equipment and fish welfare during daily inspections are already assessed in the analysis of d=21 and d=32. However, a more exposed location for the new system will increase the number of days where daily inspection is not justifiable due to harsh weather. In case of long periods of intense weather/lasting storms and no day-to-day inspection/control of the floating collar and mooring, sea cage breakdown events may occur. Hazards in this context might be fractures in the collars, damaged mooring lines from propellers, or missing securing shackle pins in the mooring interface (EI1), leading to a broken, drifting, or collapsed floating collar. Extended side ropes might snap, leading to loss or partial disconnection of the net bag. The new system has only 20 attachment points compared to 60 in the conventional system (see d=26). It is assessed that disconnection would lead to mortality instead of fish escape due to the immense impact the fish will experience when the net bag gets compressed.	6 7	2 2	4 5	E$_7$ - Breakdown of sea cage E$_7^*$ - Disconnection of net bag E$_9$ - Fish death

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**
37	On-demand operation: Net change	The removal of the net change operation will be positive in terms of structural damage and fatigue. Biofouling is a central motivation for net change, and the operation involves a lot of handling with cranes and winches. The mechanical handling equipment will experience increased loads when nets are fouled, particularly when the net is to be lifted out of water. According to Dürr and Watson (2009), when conditions are optimal for fouling, nets could increase their own weight up to 11 times within a few weeks. In conventional farming, these additional and sometimes extreme loads to handling equipment are assessed to risk level RPN=6 (L_i=4, S_i=2) for structural damage/fatigue. In terms of occupational safety over the last two decades, work operations assisted by cranes have been the largest contributor to fatalities in the industry (S. M. Holen et al., 2018b). The abovementioned study shows that seven fatalities have occurred in work operations (1992-2015). The fatalities have occurred in the categories of *man overboard* and *blow from an object/crush*, where the latter are crushed by cranes or blown when tensioned objects have been released. Additionally, misuse of a crane led to capsizing and two fatalities in 2012. The study does not distinguish between the types of operations but mentioned delousing and net change as complex/resource-demanding and central operations that use cranes and capstans. Further, a separate sister article has studied injuries in the industry (S. M. Holen et al., 2018a), where *blow from an object/crush* and *entanglement/crush* were the second and third	0 5 5	0 2 1	2 3 4	E_6- Structural damage E_1- Occupational accidents E_2- Man overboard					

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E$_i$/E$_i^*$)**
37	Continued	most common modes of injuries after *fall*. The study links operation with cranes and capstans as central causes of injuries in both categories. Based on these national statistics, the corresponding frequency levels considering a single conventional fish farm are L_i=2 and L_i=3 for fatalities and injuries, respectively. In the context of on-demand operations, after adding consequence classes, the corresponding risk level for occupational accidents leading to fatalities and injuries is assessed to RPN=6. Fatal man overboard accidents have the same risk level. Thus, considering both net change and delousing, the considerable reduction in on-demand operations is assessed to reduce the abovementioned accident frequencies by one level.									
38	On-demand operation: Delousing	As previously mentioned, the industry has seen a shift from treatments with chemotherapeutants to non-medical methods. Mechanical or thermal treatments require the fish to be crowded and pumped through a treatment system on a well-boat or a barge. This restricts free swimming and behavior control, and the fish experience the process as stressful. If the operation is not appropriately controlled, e.g., by over-crowding or too low oxygen levels, there could be repercussions of increased mortality and reduced growth. In addition, the handling might cause scale loss, fin/snout damage, and wounds. Delousing and crowding are generally associated with adverse effects on fish welfare and are, in this analysis, assessed to severity level S_i=2. The new system lowers the frequency level to L_i=4.	6 6 6	4 4 4	2 2 2	E_8- Compromised welfare E_9- Increased mortality E_{11}- Loss of growth					

Table 27: Risk impact of key differences

Key difference		Positive effect					Negative effect				
d	**Title**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**	**Justification**	**RPN$_{i,d}$**	**L$_{i,d}$**	**S$_{i,d}$**	**Hazardous event (E_i/E_i^*)**
39	On-demand operation: Net-cleaning	The net cleaning operation creates wear and tear on netting when executed, as well as the process might stress the fish and cause fouling debris to flow freely inside the cage environment, which lowers the water quality. According to (Noble et al., 2018), there are limited publications on the potential adverse effects of cleaning upon welfare. But, there are concerns and recent work that support that washed-off debris might cause short-term harm/irritation to fish gills (Bloecher et al., 2018). Although fouling abates with submergence, harmful cleaning events are expected to occur once in the production cycle or every second year. Nevertheless, the new system reduces the likelihood by one level.	5 5	4 4	1 1	E_6- Structural damage E_8- Compromised welfare					
40	On-demand operation: Lift/lower the net-bag	Handling of weights, including bottom-weight ring, has been a leading cause of fish escape, accounting for 254 000 escaped fish (11 events) according to Føre and Thorvaldsen (2017), i.e., approx 23 000 fish per event. The frequency for a conventional fish farm corresponds to L_i=3. Frequency is now assessed to be L_i=2, as lifting the bottom ring simultaneously with winches will most likely make this operation much safer in terms of escaping.	5	2	3	E_3- Fish escape	Manual handling of the extended side ropes are labor-intensive as 20 ropes must be simultaneously handled by hand during the operation. Lack of attention might result in too slack ropes, which could cause conflicts with propellers, resulting in structural damage to the rope and potentially the propulsion system. However, this new event and related negative effect yield an acceptable risk level. The removal of the net ceiling might compromise welfare and cause deaths if not appropriately controlled. As the floaters (d=10) are attached to the top rope, the roof will sink when unzipped and might create traps (net pockets) where the fish can get caught, resulting in suffering or potential death. Such net pockets might occur when the netting is not sufficiently stretched during handling.	5 6 7	4 4 4	1 2 3	E_8^*- Extended side-ropes on propeller E_6- Structural damage E_9^*- Fish caught in the ceiling E_8- Compromised welfare E_9- Fish death

B Different bow-tie illustrations

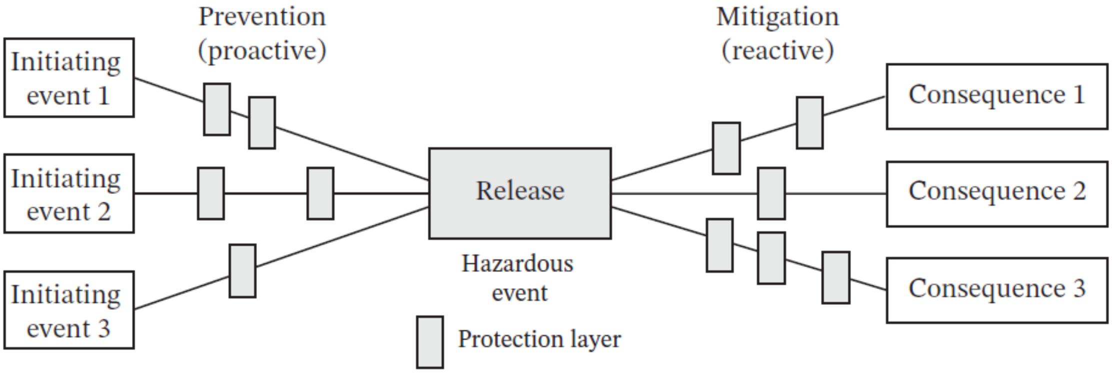
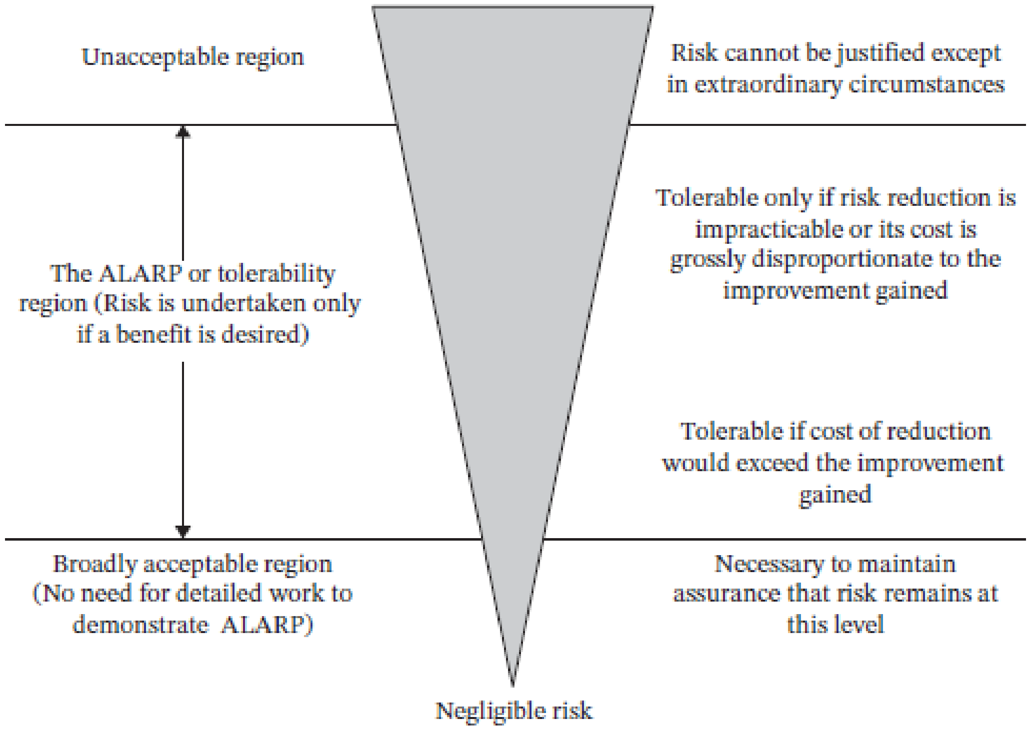
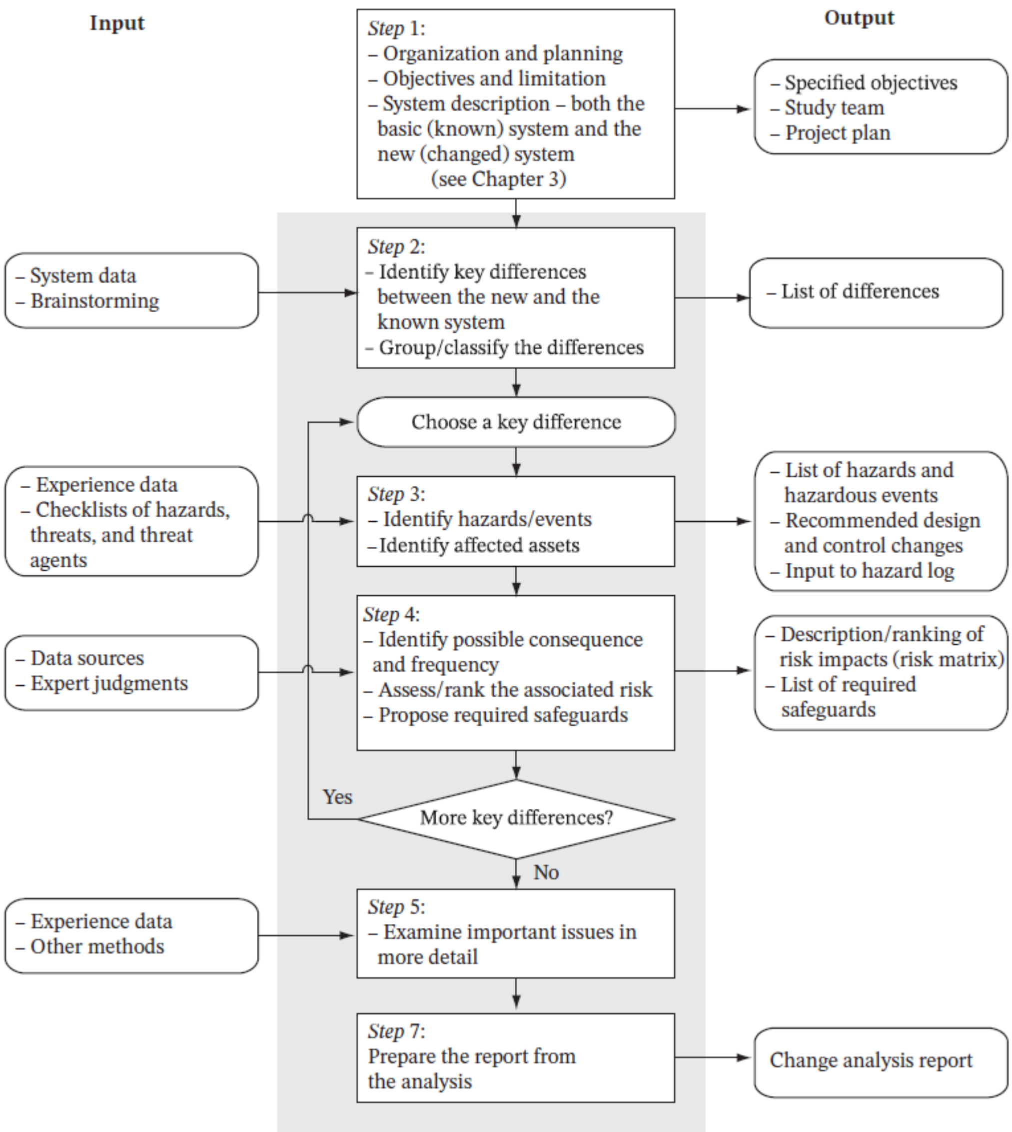


Figure 49: Source: Rausand and Haugen, 2020

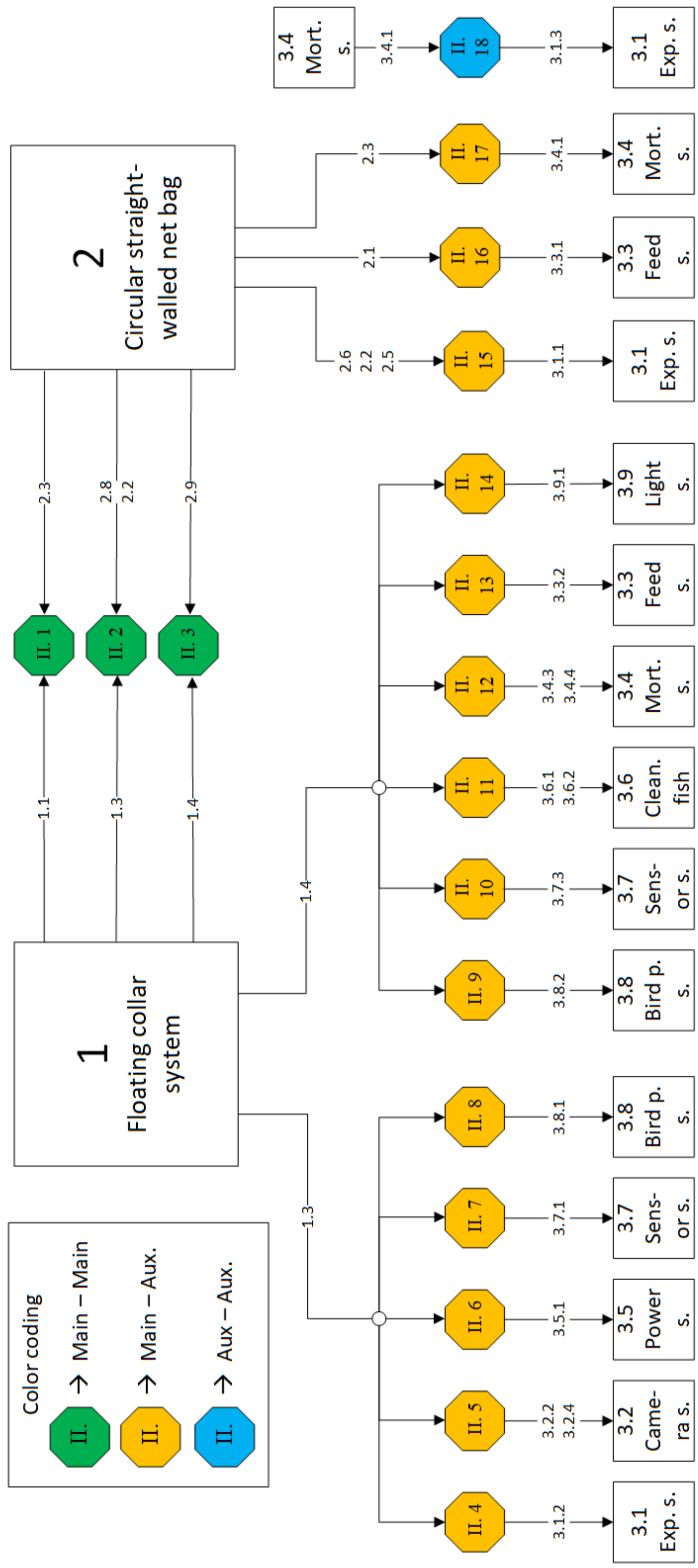
C ALARP. Source: Rausand and Haugen, 2020



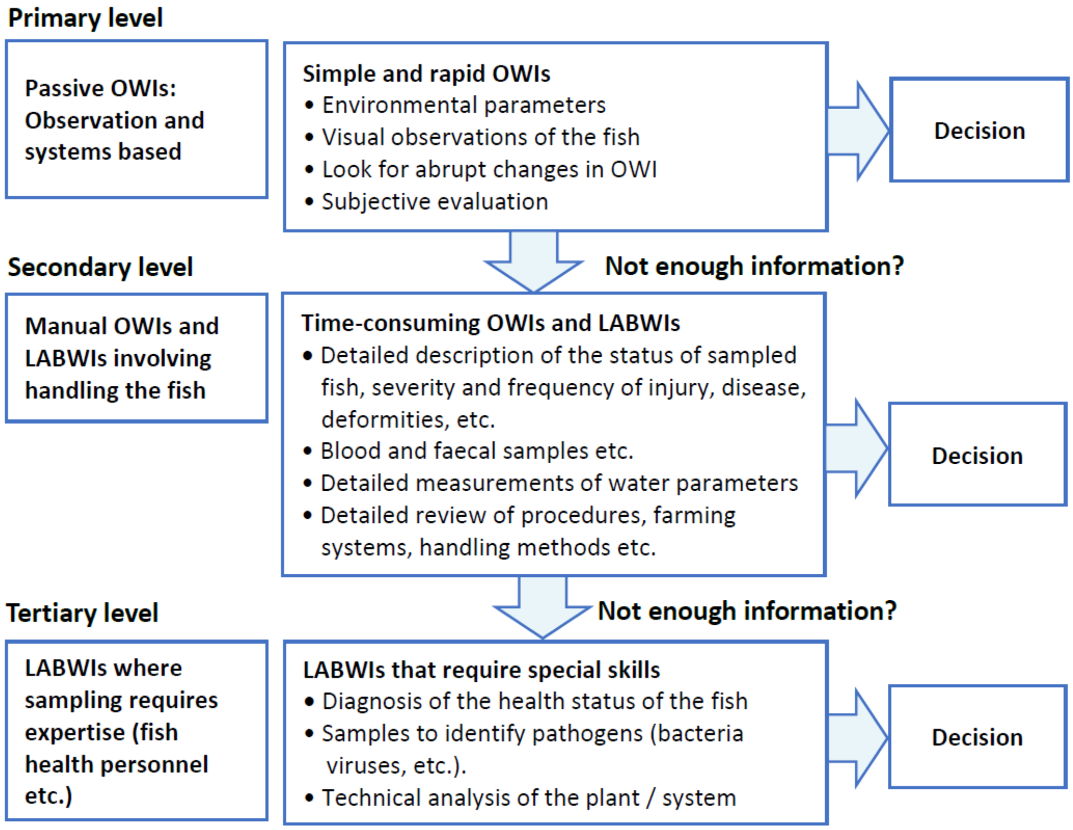
D Change analysis workflow according to Rausand and Haugen (2020)



E Internal interfaces



F Generic application of OWIs and LABWIs according to Noble et al. (2018)



G Fish farm working vessel (E24, 2016)

H Cleaner fish OWIs according to Espmark et al. (2019)

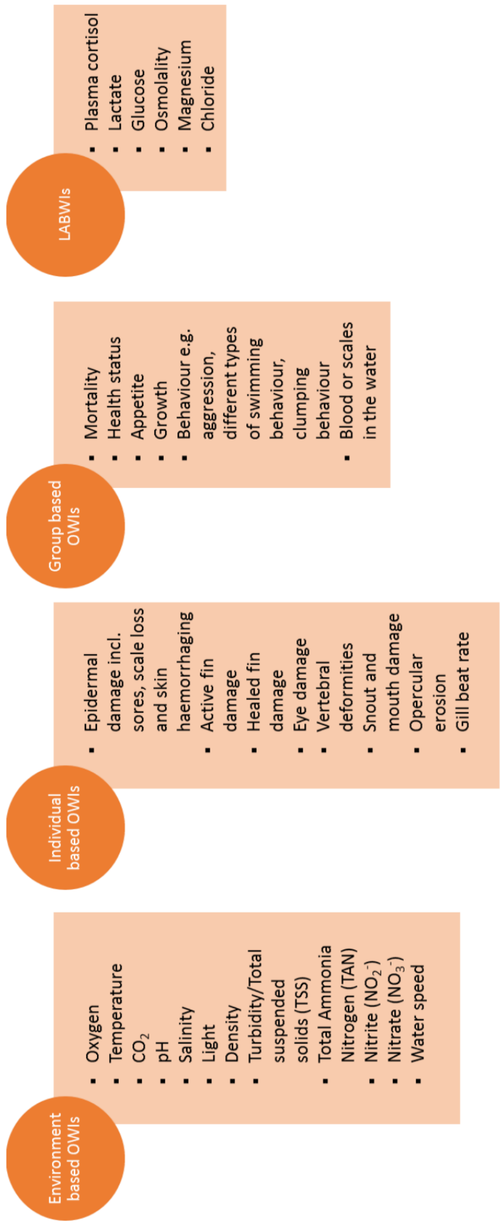
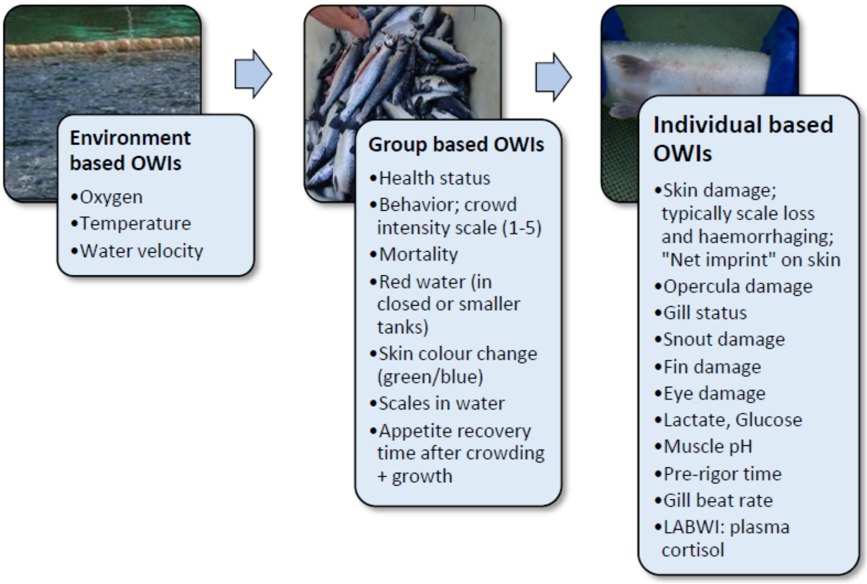
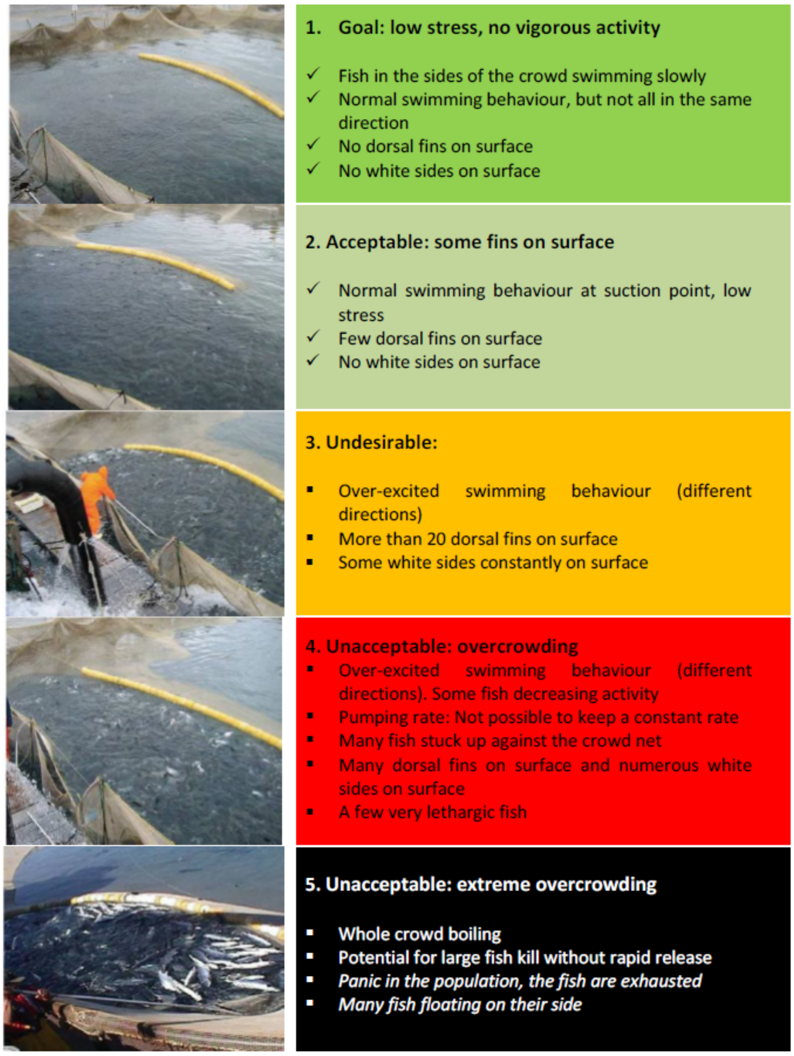


Figure 50: OWIs for Ballan wrasse

Figure 51: OWIs for lumpfish

I Fit for purpose OWIs for crowding (Noble et al., 2018)





J 3D model of the Midgard subsea system

Confidential information. Excluded from the public version.

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