Utrecht University

Assessing sea lice management strategies for the Norwegian salmon industry

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Abstract

Norwegian salmon farming has experienced rapid growth in the last few decades, and has turned into a billion-dollar industry. The Norwegian government aims to support further growth with the goal to quintuple value creation from aquaculture by 2050. Before this goal can be achieved, however, several challenges that hamper growth need to be overcome. The growing sea lice pressure is commonly perceived as the single most important challenge. Sea lice are parasites affecting salmon by feeding on its skin and blood and the economic impact they have on the industry is massive. The impact of lice is predominantly a consequence of the high density of salmon kept on farms, which allows the lice to accumulate and multiply more easily.

The Norwegian government has been regulating the growth of the salmon industry by utilizing a Maximum Allowable Biomass system and a Traffic Light System, which is specifically designed to reduce sea lice levels. The functioning of these systems is heavily debated. The industry itself also responded to the sea lice challenge by implementing different strategies to control sea lice levels but so far these have not yet proved to provide long-term solutions. Furthermore, methods that are currently used, come with numerous concerns related to fish welfare and environmental sustainability.

This study aims to assess the sea lice management strategies and associated delousing methods and cage technologies that are currently used and explored to reduce the sea lice pressure while taking into account multiple indicators. Multi-Criteria-Mapping was used to let stakeholders appraise the most common delousing methods. This is a mixed-method, software-assisted tool that allows participants to assign scores to several options, delousing methods in this case, for a number of self-defined criteria.

A total of seven participants scored the initial list of eight options and three of them proposed an additional option. It became clear that every method has its flaws and that there is no one-size-fits-all solution. It is location-dependent whether a certain method or cage technology works best, for which criteria need to be developed. The sea lice problem calls for a novel approach, in which prevention is chosen over cure. Innovative technologies like depth-based interventions, land-based farming and genetic editing might provide better long-term preventative solutions. Next to that, big data is believed to have enormous potential for managing farms in general. To support these solutions, proper coordination by the Norwegian government is pivotal.

Preface

This research was carried out as part of INTRANSIT, which is a Norwegian research center funded by the Research Council of Norway and led by the Center for Technology, Innovation and Culture at the University of Oslo. The aim of INTRANSIT is to develop new theoretical and empirical knowledge on the role of industries and industrial change in sustainability transitions. INTRANSIT focuses particularly on four Norwegian industries: aquaculture, oil & gas, maritime and manufacturing.

Next to that, this research is also my thesis project for the master's program Sustainable Business & Innovation at Utrecht University. It allowed me to put all the knowledge into practice that I gained during my years at Utrecht University. However, it was definitely not just my own expertise that made this research possible. It was built on the knowledge of the various experts that I interviewed in Norway. What is more, this research would not have been possible without the supervision of Koen Frenken. Lastly, Matthijs Mouthaan's support needs to be acknowledged. Thank you all for supporting this research and guiding me on this journey.

Finally, writing a master's thesis is not always something that students look forward to. However, most of the time, I thoroughly enjoyed conducting this research. The fact that I got the chance to go to Norway is also one of the main reasons for this. I am grateful that I got the opportunity to move abroad to get a better feel for my research, experience a different culture and meet many amazing people. I would encourage everyone to visit another country to conduct research for their thesis. You will not regret it!

Visit to a salmon farm in Bergen

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SDG:	Sustainable Development Goal
UN:	United Nations
MAB:	Maximum Allowable Biomass
TLS:	Traffic Light System
MCM:	Multi-Criteria-Mapping
NFSA	Norwegian Food Safety Authority
TA:	Technology Assessment
CTA:	Constructive Technology Assessment

1. Introduction

Globally, there is an urgent need for more sustainable food production. Accordingly, one of the Sustainable Development Goals (SDG) set by the United Nations (UN) is to end world hunger under SDG 2 (*‘End hunger, achieve food security and improved nutrition and promote sustainable agriculture’*) (UN, 2015). Since 2015, the numbers of undernourished and malnourished people have been growing as the earth’s population approaches 10 billion people. Innovative solutions are necessary to produce more food and improve nutrition in a sustainable manner (FAO, 2020).

Fisheries and aquaculture are believed to be food sources that can contribute substantially to this goal. Fish and fish products coming from fisheries and aquaculture are recognized among the healthiest foods and are much less impactful on the natural environment than meat or dairy products (FAO, 2020). Given that wild fish stocks are to a large extent overexploited, growth in fish supply is expected to come from aquaculture (Nesset & Tusvik, 2017). During the last decades, this part of the seafood industry has experienced tremendous growth globally, as can be seen in Figure 1 (FAO, 2020). However, before significantly enhanced volumes of seafood can be produced sustainably, impacts on environmental sustainability, fish welfare and human health need to be considered (Stentiford, 2020). These developments are also at the core of SDG 14 (*‘Conserve and sustainably use the oceans, seas and marine resources’*) (UN, 2015).

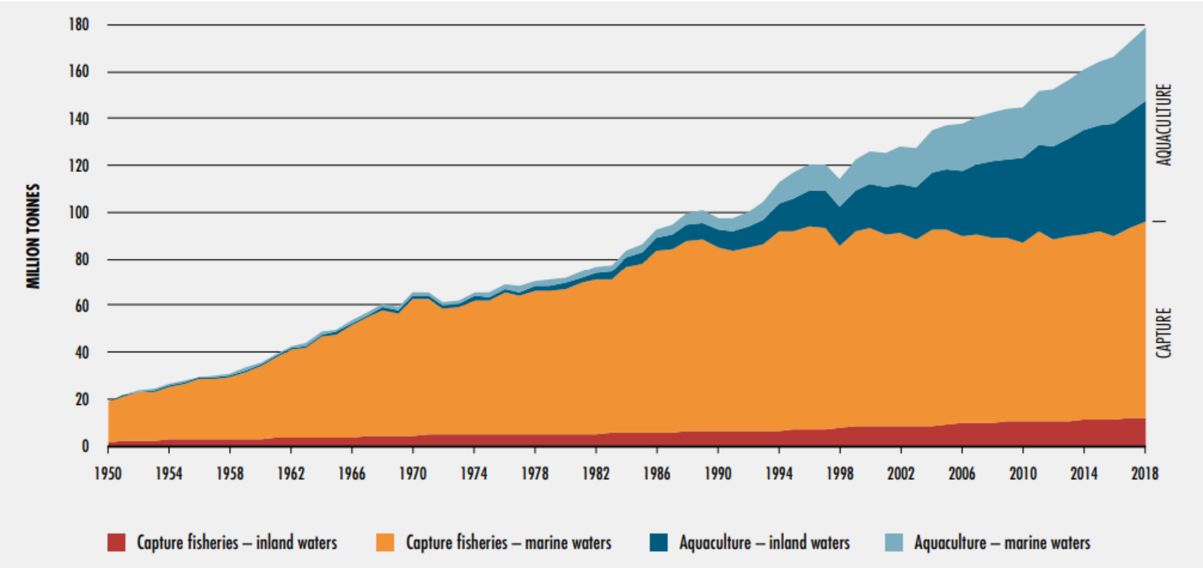

Figure 1: World capture fisheries and aquaculture production (FAO, 2020)

Salmon farming is among the most successful aquaculture industries. It has experienced a production growth in recent decades that is higher than aggregate aquaculture production, despite being a high-value product (Asche et al., 2014). The production of Atlantic salmon increased from 1.4 million tonnes in 2010 to 2.4 million tonnes in 2018. This is a 4.5% share of the total amount of fish produced in 2018 (FAO, 2020). Currently, Norway’s aquaculture sector for salmonids is the largest in the world, accounting for over half of the world’s salmon production in 2021 (Mowi, 2022). Among other things, this is a result of favorable natural conditions and relatively simple and low-cost technology. In this way, Norway can exploit the advantage of free ecosystem services (Iversen et al., 2013). Salmon farming in Norway is typically done by keeping the salmon in floating sea cages or net pens anchored in sheltered bays or fjords along a coast (see Figure 2).

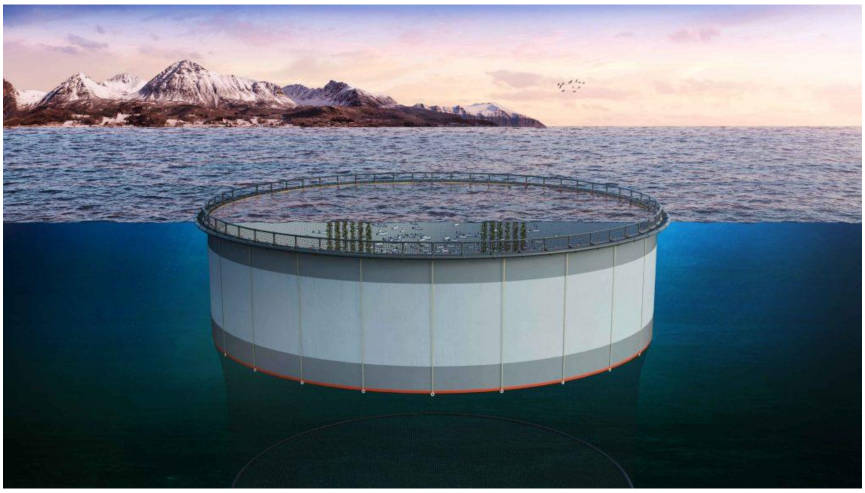

Figure 2: Open net-pen salmon farm

The Norwegian government is investing heavily in this industry to maintain its position and aspires to quintuple production value from aquaculture by 2050 (The Norwegian Government, 2021). However, several risks are associated with scaling up the seafood industry. Environmental issues, as well as fish welfare problems and production challenges, hamper growth and need to be overcome to be able to pick the fruits from this promising industry. Sea lice infestation has a hand in all these challenges and currently stands perhaps as the single most important challenge to the industry (Hjeltnes et al., 2017). This parasite feeds off the salmon's flesh and skin and the economic impact on the salmon industry is estimated to be US$301 million in 2006, which is equivalent to 8.81% of the industry's total production value (Abolofia et al., 2017). The Norwegian government acknowledges this problem and currently uses the Maximum Allowable Biomass (MAB) and the Traffic Light System (TLS) to govern the issue (Hersoug, 2021).

The industry has been doing extensive research to find proper control methods. This has resulted in different types of innovations aimed at lowering the sea lice pressure, among which are: chemicals, mechanical methods, cleaner fish and selective breeding. So far, these innovations have not yet managed to control sea lice levels. At the roots of this issue lies the adaptive nature of the lice. Through natural selection, the louse has managed to develop characteristics that make certain methods obsolete (Coates et al., 2021). For example, sea lice have become almost completely resistant to several chemical treatments. Subsequently, different types of methods that target the lice from different angles are now being implemented simultaneously. This currently seems like a necessity for reaching acceptable sea lice levels (Coates et al., 2021).

Next to the actual effectiveness, other factors are also essential to consider. Chemicals are not considered environmentally friendly, leading to concerns about bioaccumulation and effects on non-target invertebrate species (Burridge et al., 2010). Mechanical and thermal methods are, for instance, stressful for the host fish, despite being a fairly effective substitute for chemical treatments (Overton et al., 2019a). The use of cleaner fish is criticized due to their poor living conditions on farms and their debatable effectiveness (Barrett et al., 2020). Thus, sea lice puts constraints on further growth as well as providing a burden for animal welfare and environmental sustainability. In all, this shows that sea lice put enormous pressure on the salmon industry. Before implementation of new strategies, it would help both government and industry to gain an overview of different methods and their likely effects in terms of various performance indicators, as to come to a more holistic understanding of preferred strategies in the short and long term. Accordingly, the research question holds:

What management strategy should be implemented in order to reduce the sea lice pressure on the Norwegian salmon industry?

This research attempts to gain insights into the strengths and weaknesses of methods used to reduce the impact of sea lice. This is done by assessing these methods on a number of variables defined by different stakeholders. Multi-Criteria-Mapping (MCM) was used as a tool to create an overview of stakeholders' perceptions (Stirling & Mayer, 2001). By gathering information from different stakeholders, a more holistic overview of possible solutions can be created. This information can help industry stakeholders incorporate additional variables such as fish welfare and environmental problems into their sea lice management strategies. Next to that, it can be used by the Norwegian government to design structures or policies to be able to govern the industry in a manner that benefits the society as a whole.

The outline of this study is as follows. The next section provides more detailed background on sea lice and an overview of the different methods that are used to control sea lice. The subsequent section presents the methodological framework through which the research question is approached. Hereafter, the study elaborates on the results and analysis. Finally, the study provides a conclusion and discussion.

2. Theoretical background

2.1 Sustainability in (Norwegian) aquaculture

As mentioned in the previous chapter, even though the aquaculture industry possesses huge potential, it comes with many challenges. So far, aquaculture has succeeded in providing extensive food resources while also achieving the critical goals of environmental, economic, and societal sustainability (Boyd et al., 2020). However, the extreme rate at which the aquaculture industry develops asks for an extensive evaluation of the prospects and potential unwanted environmental side effects. This is necessary to stay aligned with SDG 14 (‘*Conserve and sustainably use the oceans, seas and marine resources)* (UN, 2015’). Sustainable use of resources also known as sustainable development is a concept that might be interpreted in different ways in different sectoral contexts. For a definition tailored to aquaculture, the following statement (Boyd et al., 2020) can be referred to: “*The goal of sustainable aquaculture is to provide a continued supply of farmed aquatic nutrients beneficial for human sustenance without harming existing ecosystems or exceeding the ability of the planet to renew the natural resources required for aquaculture production.”*

Sustainability generally comprises three pillars: social, environmental and economic. Sustainability and sustainable development require the incorporation of all three. How these pillars should be ideally balanced is debatable though. Humans tend to prioritize the more humanistic-based economic and social pillars to preserve their own kind. Furthermore, competing interests of stakeholder groups can make it difficult to find a balanced representation of these pillars (Boyd et al., 2020).

This issue is illustrated by the current case of aquaculture in Norway. The goal of the Norwegian government to quintuple value creation from aquaculture by 2050, is in essence an economic target. However, it cannot be achieved without taking the other pillars into account, because whether aquaculture production should be managed in an environmentally responsible and sustainable fashion is no longer open to debate (Engle & D'Abramo, 2018). Thus, the government faces the challenge of how to regulate the industry most effectively, allowing growth and innovation while at the same time securing environmental sustainability (Hersoug, 2021). Among the biggest challenges that the industry is currently facing is sea lice pressure.

2.2 The sea lice problem

In the last few decades, the Norwegian salmon aquaculture has encountered major difficulties due to a growing number of sea lice. The *Lepeophtheirus salmonis* is the most threatening sea lice species to the farmed salmon in Norway. To know how this species affects the salmon, it is important to know about the lifecycle of the louse. The louse has a lifecycle of 10 different stages: three free-swimming, four parasitic and three mobile phases (Costello, 2006). The louse can, in the adult life stage, attach themselves to the different body parts of the salmon and feed on their skin and underlying tissue. This results in a reduced appetite and growth, external wounds, increased stress and reduced vitality due to vulnerability to infections and diseases (Abolofia et al. 2017). Sea lice infestations are a natural phenomenon that has affected natural salmon populations for many years. However, the conditions of aquaculture farms make it easier for the lice to accumulate and multiply.

This is a result of the farms being stocked at a higher density than wild salmon populations (Science for Environmental Policy, 2015).

The salmon industry has reacted to this trend by implementing methods aimed at lowering the impact sea lice have on salmon. Over the last decades, different types of methods have been implemented to achieve this (Figure 3). Initially, cleaner fish were used to try to get rid of the lice, in what was then perceived as a relatively natural manner. These cleaner fish feed upon the lice and thereby lower the chances of the salmon being affected by them. Another frequently used method is the use of chemotherapeutants (chemicals), on which salmon aquaculture has relied throughout most of its history. Several chemicals have been used, such as azamethiphos, pyrethroids, emamectin benzoate, hydrogen peroxide and benzoylphenyl ureas. Chemicals have proven to be highly effective in some cases, but as stated earlier, their efficacy tends to decrease as the parasites develop resistance to certain chemicals. Relatively new non-chemical methods include depth-based interventions, thermal delousing, mechanical delousing, freshwater delousing and genetic innovations (Coates et al., 2021).

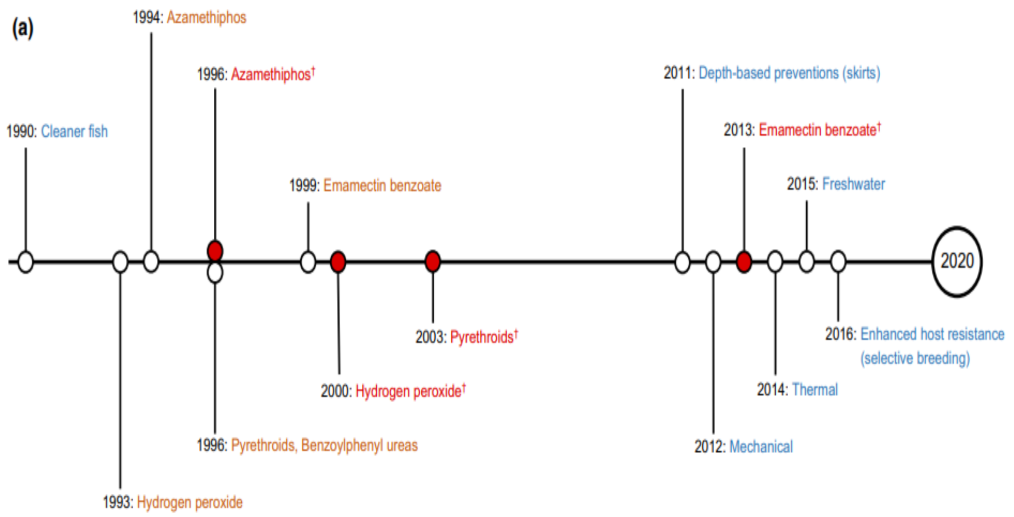

Figure 3: History of sea lice management strategies (Coates et al., 2021, p. 6)

2.3 Governmental regulations

The Norwegian Government has governed the growth in aquaculture early on (Hersoug, 2021). In 1973, licenses were handed out to farmers, which included a net pen volume per license of 3000 m^3, which was increased to 12,000 m^3 in 1988. The idea behind this system was to keep the industry small in size because investors had lost huge sums of money in the 1960s due to overproduction. Nevertheless, the adjustments in size allowed the industry to grow rapidly with barely any limitations. In 1996, feed quotas were introduced to be able to more directly control the growth of the industry. This system was replaced in 2005 with a Maximum Allowable Biomass per cage. The idea underlying this system would improve fish welfare and biological sustainability (Hersoug, 2021).

As mentioned earlier, the growing salmon industry also resulted in the growing presence of sea lice. The Norwegian government felt obligated to oversee the manner in which lice infestations were dealt with. Since 1997, sea lice infection has therefore been regulated to reduce the harmful effects on both farmed and wild fish (Abolofia et al., 2017). The Norwegian Food Safety Authority (NFSA) checks whether farmers have routines for lice prevention that include plans for counting lice, methods for treatment against lice, evaluation of treatments, use of cleaner fish and regional cooperation (Norwegian Ministry of Trade, 2012). These regulations included a maximum number of sea lice per fish and farmers being obligated to report data about sea lice populations on their farms. Until 2017, the infection threshold was set at 0.5 for adult females and 3 for adult males and pre-adult lice for the period of January 1st – August 31st and respectively 1 and 5 for the rest of the year. When the threshold was exceeded, the producer was obligated to medically treat or slaughter the fish within 2 weeks (Abolofia et al., 2017).

Since 2017, a new regulatory system has been implemented, which is called the 'Traffic Light System'. It divides the country into 13 production areas and assesses them on a number of sustainability indicators (Figure 4). Based on the performance of these criteria, a color code is assigned to the respective area (green, yellow, or red). This code determines whether the production area is allowed to increase its production (green light), freeze its production (yellow light) or required to reduce production (red light). Production can be increased by a maximum of 6% every 2-year period (The Norwegian Government, 2015). This system encourages the producers to take responsibility for their production environment and rewards them with possibilities for growth (Nrk.no, 2017).

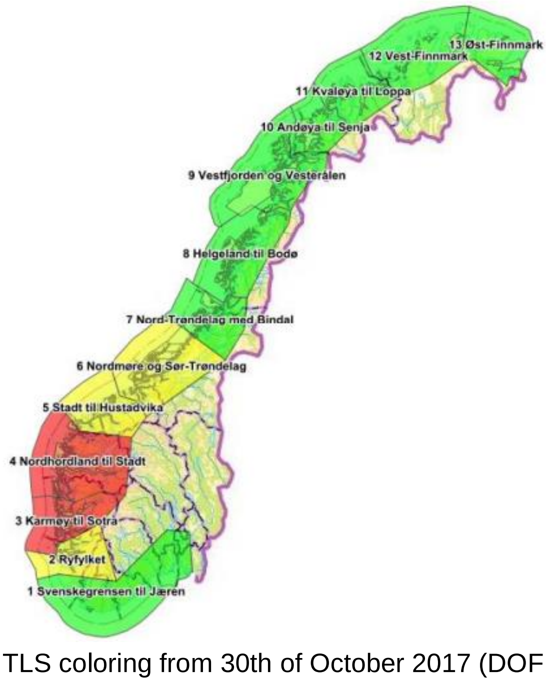

Figure 4: TLS coloring from 30th of October 2017 (DOF, 2019)

2.4 The most common delousing methods

Delousing methods can be categorized through organizing them by the moment in time that they are used. There are immediate, continuous, or preventative strategies, which target different stages of the life cycle of the lice. Immediate strategies remove lice during an acute treatment process. Continuous strategies are used to remove lice over a longer period and a while after treatments are applied. Preventative strategies prevent larvae from attaching to a host (Coates et al., 2021). For the sake of comparison, the following archetypes of delousing methods are used: chemotherapeutants, mechanical delousing, thermal delousing, freshwater delousing, cleaner fish, depth-based interventions and natural resistance.

Chemotherapeutants

Several chemicals have been used to get rid of the lice over the years, which can also be observed in Figure 3 (Coates et al., 2021). Where the use of chemicals turned out to be an efficient method in some cases, generally, the efficacy has decreased dramatically over the course of the years due to the development of resistance among lice (Aean et al., 2015; Jones et al., 2013). For instance, the efficacy of hydrogen peroxide has dropped from 75% to 8% in 8 years' time (Treasurer et al., 2000). Only benzoylphenyl has proven to be immune to resistance development by lice (Aaen et al., 2015).

Multiple factors have facilitated the widespread establishment of resistance among sea lice: strong selection pressures, high louse gene flow, low fitness costs of resistance and the minimal effect of wild host refugia. The use of a low number of these chemotherapeutants has given the lice the opportunity to develop gene characteristics that make them resistant to these chemicals. This makes it that the efficacy has decreased over the years. Despite this development, farmers still keep using them in increasing quantities. Next to that, the gene flow of the louse is known to be spreading rapidly over a large number of individuals over a large geographic scale. As a result, resistance among sea lice to certain chemicals has spread to many populations in Scandinavia before spreading across the North Atlantic areas (Coates et al., 2021). Also, no fitness costs have been observed following gene adaptation to the chemicals, which means that the chemicals are not holding them back in any way. Lastly, wild hosts can serve as refugia for sensitive lice, but a lack of wild salmon in Norway (farmed salmon outnumbered wild salmon 257: 1 in 2017) diminishes this advantage (Thorstad et al., 2020).

Mechanical delousing

Mechanical methods include systems where the salmon are pumped through. In this system, jets of pressurized water, turbulence and/or brushes are used to remove the lice from the host. Besides the standard mechanical delousing sessions, this usually also occurs when salmon are transferred between pens or handled during sampling (Bui et al., 2020a). Currently, mechanical delousing comprises 25% of all immediate strategies (Coates et al., 2021).

Thermal delousing

Thermal delousing entails exposing the lice to warm temperatures up to 36°C for approximately 30 seconds. Salmon are bathed in warm water for a short period of time by automated systems, which forces the lice to detach from the host. This measure comprises more than 60% of all immediate strategies (Overton et al., 2019a). It can, however, result in poor welfare outcomes for the fish (Poppe et al., 2018). Between 2012 and 2017, warm thermal treatments resulted in increased mortality for 31% of all treatments. In contrast to warm water, cold water treatments are now also being considered a promising treatment method. This could possibly increase efficacy, but may also pose additional welfare risks (Overton et al., 2019b).

Freshwater delousing

Since lice are sensitive to low salinities, exposing them to freshwater is another way to remove lice from their host. Similar to thermal delousing, this strategy involves salmon being bathed in freshwater for a few hours in an attempt to detach them (Groner et al., 2019). Only 5% of the immediate lousing measures comprise freshwater delousing (Sommerset et al., 2020) and therefore lice have not yet developed resistance to freshwater (McEwan et al., 2015). There are concerns, however, that the lice could develop improved freshwater tolerance when freshwater delousing is to be used on a larger scale.

Cleaner fish
Cleaner fish can be a very natural way to decrease lice populations as they remove lice in a natural manner. The lumpfish (*Cyclopterus lumpus*) and multiple species of wrasse (*family Labridae*) are used to remove the lice from salmon. They were first used in the 1980s, and now more than 60 million fish are stocked on fish farms worldwide (Skiftesvik et al. 2013; Imsland et al. 2014; Leclercq et al. 2014). However, little is known about the exact efficacy of this fish for decreasing lice populations on farms. While cleaner fish have put selective pressure on the lice in some cases, evidence about the degree to which they really pose a threat to the lice across environmental conditions seems to be lacking (Overton et al., 2020).

Depth-based interventions
Depth-based interventions include methods that are based on the water level at which sea lice thrive. The sea lice are usually located at the shallower depths in the water column and therefore a solution could be to force the salmon to swim below these depths. Both skirts and snorkel cages technologies are depth-based interventions used to segregate lice from the salmon population (Barrett et al., 2020). Production cages with plankton nets have proved to reduce the exposure to lice, as they prevent access of louse larvae at certain depths (Grøntvedt et al. 2018). Snorkel cages separate both species by submerging salmon beneath the lice layer. Tubes to the surface are accessible to the salmon to refill their swim bladders, hence the name 'snorkel cage' (Geitung et al., 2019). Both of these technologies have proven to reduce lice infestation, although they are dependent on environmental conditions and swimming behavior (Samsing et al. 2016; Bui et al. 2020b).

Natural resistance
Another method to lower the infestation of lice could be to improve the natural resistance of salmon to lice. Salmon with immunologically defensive mechanisms against lice are able to reject a large number of parasites right after attachment (Braden et al., 2015). Currently, this is done in two different ways: by providing salmon with functional feeds and through selective breeding. Special food can induce a heightened immune response and thereby lower the infestation by 50%. Where functional feeds only offer temporary protection, selective breeding offers salmon protection for a longer period of time. Strains that are resistant to lice have been offered by salmon companies since 2016 (Coates et al., 2021). Selective breeding over a time period of 10 generations has the potential to reduce the frequency of chemical delousing by 60% (Gharbi et al., 2015). Which also goes for these measures, is that they are susceptible to adaptations of the lice itself. A more radical measure is to use gene-editing technologies to integrate part of the genes of Pacific salmon species, which have proven to be more resistant to lice, into the Atlantic salmon species (Barret et al., 2020). The possibilities for this strategy are currently still being explored for commercial use in the future.

2.5 New methods and combining methods

As has become clear from the flaws of the methods described in the previous section, not one method clearly stands out as the ultimate solution yet. Unwanted side effects on the environment as well as impact on salmon welfare and debated effectiveness are points of discussion. This makes it interesting to explore new innovative methods with less undesirable side effects. Furthermore, the fact that the lice can adapt quickly to different methods makes it hard to design a management strategy that can be effective in the long term. To increase effectiveness, it might be better to combine different methods in a way that they, rather than targeting the same stage, target different stages of the lice life cycle.

3. Methodology

3.1 Research perspective: Technology Assessment

The study takes a Technology Assessment (TA) perspective in order to assess delousing methods in Norwegian salmon farming. TA aims to identify and assess eventual impacts of technologies early to guide policy making and decision-making in general (Rip, 2015). This is in line with the goal of this study, which is to consult the government and other stakeholders in decision-making by evaluating several technologies on different indicators.

TA was initially created as an attempt to predict the course of the development of technology and all of its societal effects. However, in the 1970s and 1980s, this assumption often turned out to be problematic. Crucial developments, such as the oil crisis, were not foreseen and made some assessments worthless (Van den Ende et al., 1998).

New forms of TA emerged, which aimed at strengthening the position of specific actors in a complex process of socio-technical decision-making (Van den Ende et al., 1998). Next to writing a report, new-style TA research also included a discussion with the relevant actors. Four forms of new-style TA can be distinguished: Awareness TA, Strategic TA, Constructive TA and Backcasting. Awareness TA is about forecasting technological developments and their impacts to avoid undesirable consequences. Strategic TA tries to support specific actors or actor groups in formulating a strategy for a certain technological development. The aim of Constructive TA is to shape the course of technological development in a socially desirable direction by broadening the decision-making process. Backcasting comprises development of desirable scenarios and necessary innovation processes to achieve this (Van den Ende et al., 1998).

Constructive TA seems to be the most fitting approach for a number of reasons. One of the goals of this study is to look for a management strategy that takes a wide variety of criteria into account, proposed by numerous stakeholders, and thereby “broadening” the decision-making process. Furthermore, the idea that technological developments can be shaped in a way that they support societal goals is very much in line with the goal of this research (Van den Ende et al., 1998): developing a strategy that benefits society as whole. Lastly, this study aims to assess older as well as newer technologies, which is also one of the characteristics of Constructive TA (Rip, 2015). Thus, considering this study aims to shape a socially desirable future that is supported by a variety of stakeholders, Constructive TA seems the most fitting approach.

3.2 Method: Multi-Criteria-Mapping

Constructive TA is more of a research approach than a method in itself. Therefore, an actual method that is applicable to this study still needs to be defined. The following features need to be incorporated in the method. Both quantitative and qualitative approaches have important contributions to offer to decision-making and should be part of the method. Through a quantitative approach, different options can be appraised, whereas qualitative components can reveal underlying reasons that shape people’s perceptions more clearly. The earlier mentioned criteria are also crucial for articulating a management strategy and should be able to be assessed through the method. Lastly, the aim of the study is not to identify a single best option, but to identify the reasons that shape people’s perceptions. This aspect should also be included in the method.

MCM is a multi-criteria decision analysis tool in which all of these elements are incorporated. It is a software-assisted method used to assess different options for areas of science and technology (Stirling & Mayer, 2001). This assessment is done by analyzing the respective strengths and weaknesses of different options under participant-defined criteria. Rather than identifying a 'best' course of action, its aim is to identify the different underlying reasons that influence people's perceptions and valuations of different options. It includes linking qualitative and quantitative information from different experts on the issue. This is done by systematically evaluating the stakeholders' viewpoints on the options and mapping them out (Coburn et al., 2019). The result is an array of open qualitative and structured quantitative information that sketches a rich picture of the conditions under which options may or may not be preferred (Jones, 2011; Stirling & Mayer, 2001). The MCM process can be broken down into six distinct phases:

1) Designation of technology area
2) Research into scientific and policy literature
3) Identification of participants
4) Definition of options
5) Individual interviews
6) Analysis

The first two of these steps are covered in the literature review discussed above. The remaining phases are tailored to the MCM process (Jones, 2011; Stirling & Mayer, 2001).

3.2.1 Focal goal

Central to the MCM is a certain focal goal, which is a clear and commonly shared aim for a variety of alternative options. It can be a social function or objective, for which the options for achieving it forms the base of the MCM (Coburn et al., 2019). The focal goal of this study is the following: reducing the sea lice pressure in Norwegian salmon farming.

3.2.2 Identifying participants

MCM aims to gather information from different experts and stakeholders of a certain policy debate. It is important to take the perspectives into account of relevant actors that play a role within the socio-political governance context (Stirling & Mayer, 2001). Based upon the initial review of the policy, scientific and historical literature discussed, several stakeholder groups have been defined. These include:

1. Salmon farmers
2. Governmental institutions
3. R&D institutions
4. Start-ups
5. Other organizations (Innovation clusters, wildlife conservation groups, suppliers, etc.)

Before participants were approached, an extensive overview was created with the most relevant actors in the industry. This overview can be found in Appendix I. Thereafter, a diverse group of people was approached in order to include the expertise of different people from the salmon sector. The initial set of candidate participants was asked for leads to other potential interviewees. The final set of seven participants was arrived at through this kind of snowballing process (Coburn et al., 2019). An overview of the stakeholder groups of these participants can be found in Appendix II. It was hard to label the participants due to the fact that participants switched jobs a few times. For instance, a couple of participants have been salmon farmers themselves in the past, but are now active in other kinds of organizations. Finally, the aim was to include a higher number of participants, but multiple potential participants declined or did not respond. This could be due to the covid situation putting pressure on people working in the salmon industry. The lack of participants was partly compensated for by the lengthy interviews in which in-depth information was extracted.

3.2.3 Defining the options

The first stage in MCM concerns formulating options that vary depending on the context of the research. These options comprise alternative ways forward for the problem and can be policy options or diverse pathways. It is important that each option is sufficiently distinct from the others in that it addresses various aspects of the issue (Jones, 2011; Stirling & Mayer, 2001). The following options can be distinguished: *core*, *discretionary* and *additional*. The core options are pre-defined by the interviewer and evaluated by all participants, which ensures a systematic and structured comparison across all interviewees. This means that pre-defining these core options should be done with great care. Discretionary options are used to 'round out' the scope of the options and participants have the choice to evaluate them. Lastly, the interviewee has the freedom to add an additional option in the case that he feels an unmentioned option is important to consider as well (Jones, 2011; Stirling & Mayer, 2001).

The core options can be defined by doing prior research or engagement processes. The following methods were used to define the initial set of core options: literature research, stakeholder analysis and scoping interviews (Coburn & Stirling, 2016). The first step in defining the core options was doing rigorous literature research. The second step consisted of a review by experts during scoping interviews. Afterward, the initial list was tweaked slightly in order to make the options more concise and distinguishable from each other. On top of that, the options were adjusted so that they are formulated in a 'neutral' way, to avoid prejudices and preferences based on the description. The final set of core options can be found in Appendix III.

3.2.4 Scoping interview

As mentioned earlier, scoping interviews were done to gather some more general information about the focal goal, the core options and relevant participants. It was important that each individual was contacted well in advance of the MCM interview in order to discuss the general context and aims of the MCM exercise as a whole and to be sure that these are both understood and satisfactory. These 'scoping interviews' are essential in ensuring that participants are as well informed and comfortable as possible about what is expected of them and the uses to which their inputs will be put, as well as in saving precious time in the engagement process. It also gives a chance to fine-tune particular design features of the exercise (Coburn & Stirling, 2016).

3.2.5 Data protection

To ensure that the collected data is used in an appropriate way and protected accordingly, permission was asked and granted by the Norwegian Center for Research. This is obligatory for research projects that are carried out under the supervision of the Norwegian Government. Before every interview, consent was asked for processing individual data of participants.

3.2.6 MCM interview process

After the goal is defined and the participants and options are determined through scoping interviews, the MCM interview process starts. Figure 5 illustrates the steps that take place in the interview. It is an iterative and cyclical process. Participants can return to earlier steps at any time and can repeat the whole process freely (Coburn et al., 2019). A MCM interview typically lasts between 1h 50 min and 3h 10 min:

1. Starting the interview (10-20 min)
2. MCM step one: identify options (10-20 min)
3. MCM step two: define criteria (10-20 min)
4. MCM step three: assess scores (60-90 min)
5. MCM step four: assign weights (10-20 min)
6. Winding up the interview (10-20 min)

Due to time restrictions, it is usually not feasible to do this. The aim for this study was to take approximately 1h 30 min for every interview.

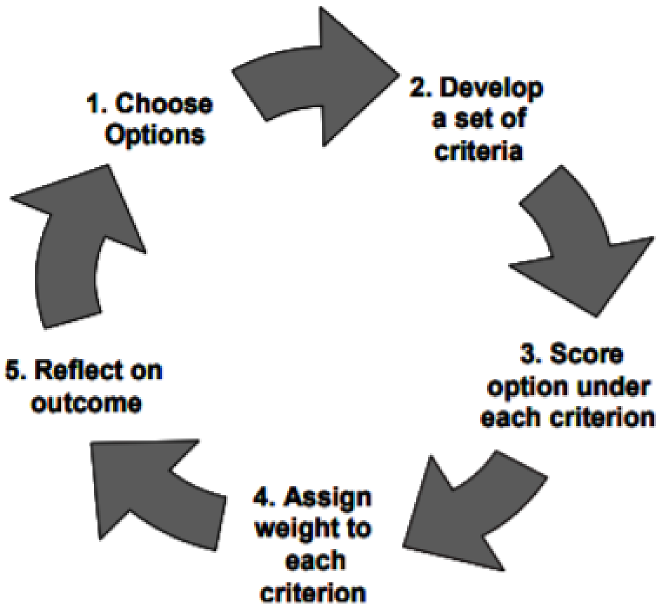

Figure 5: Stages of an MCM interview (Jones, 2011)

Each stage can be summarized as follows (Coburn & Stirling, 2016; Jones, 2011):

1) Choosing options: the initial set of options is discussed and the participants are asked if additional options should be included.

2) Develop a set of criteria: participants are asked to define criteria that they think are most suitable to evaluate the options.

3) Score options under each criterion: participants are asked to evaluate each of the options based on how well it performs under each individual criterion. They are asked to assign both a pessimistic and optimistic score to each option on a scale of 0-100 and for their reasoning behind the scores.

4) Assign a weight to each criterion: participants are asked to assign relative weightings to the criteria. Here participants can express the relative importance of each of the criteria they have defined. They are encouraged not to think about the rank order of the criteria, but the relative importance of the criteria in terms of the assessments of options themselves.

5) Reflect on the final outcome: the final map of performance rankings, as well as the whole process, is reflected on. This gives the participant the opportunity to see if the outcome accurately reflects the view they initially had about the options.

3.2.7 Analysis of the data

The MCM study will produce quantitative and qualitative data outputs. The last phase of the process is to analyze these outputs through the following steps (Coburn et al., 2019):

3.2.7.1. Preparing and loading data for MCM analysis

It is crucial that qualitative and quantitative data are considered together. In this way, the interpretation is mutually informed by each other. Qualitative data consists of three types, which are mutually informed by each other:

- Names and definitions developed for the pre-defined options;
- Statements made by the participants that were noted in the MCM software (perspectives on the core options, additional options, criteria, scoring, weighting and reflections);
- Audio recordings, later transcribed as text transcripts.

Quantitative data consists of four types:

- Numerical values for pessimistic and optimistic scores;
- Intervals between pessimistic and optimistic scores (uncertainties);
- Weights attached to each of the criteria;
- Ranks that are computed by the software to express the performance of each option.

3.2.7.2 The elements of MCM analysis

Aims

The aim in the analysis is to explore the different possible pictures of the results in the MCM appraisal. This concerns two kinds of value:

- Direct: Displaying the patterns in the performance of different options;
- Indirect: Providing background understanding with respect to the reasoning of scoring certain options favorably or unfavorably.

Stages in the analysis
In essence, a MCM analysis consists of an iteration around the groupings of data. This process includes steps such as becoming familiar with the material, exploring the consequences of different assumptions, checking the qualitative data for different groupings using reports and taking a measured and cautious approach to representing findings.

3.2.7.3 Setting up MCM analysis using the MCM software

Before the data can be analyzed, all the data needs to be synchronized. This is done by uploading all the quantitative and qualitative data into the analysis section of the MCM software.

3.2.7.4 Defining perspectives, issues and clusters

In order to make the data easier to analyze, groupings have been made. Due to the number and nature of participants, it was not sensible to group them into perspectives. The proposed criteria were grouped into issues and some of the options were grouped into clusters.

3.2.7.5 Generating and interpreting reports and charts

First, a general report is generated that includes the average rankings of all options, which is used to do some general observations. Next, reports for uncertainty, ambiguity and weightings were generated, accompanied by a possible explanation for the results that stood out the most. The normalization and aggregation procedures can be retrieved from Appendix IV.

Uncertainty:
The mean ratio uncertainty is related to the length of the interval between the pessimistic and optimistic scores assigned by the participants. It is calculated by taking the median of the pessimistic and optimistic scores and calculating the ratio between this and the corresponding interval uncertainty.

Ambiguity:
Ambiguity is related to the scale of the differences between individuals in their option assessments. It basically reflects the degree of collective disagreement for each of the options.

Weightings:
These values indicate the mean aggregate weightings in a given set over different groups of criteria (issues).

Thereafter, the issues that were formed earlier are used to generate reports with aggregating scores per issue. The results of these reports are discussed in detail with the qualitative data. Quotes are used as a way to clarify specific results.

3.2.7.6 Analyzing qualitative data

During the analysis phase, the options are at the center of attention. After discussing the issues, the viewpoints on every option are explored extensively. This is structured by covering all the different criteria and the viewpoints of the participants on these options. Similar and contrasting viewpoints are considered and elaborated on with quotes.

3.2.7.7 Analyzing proposed solutions

The open-ended question about the participant's vision of solving the sea lice problem produced qualitative data. These answers are summarized and discussed by each of the participants individually.

3.2.7.8 Putting it all together

Finally, from all quantitative and qualitative results several conclusions can be drawn, and presented as take-aways. These take-aways are the foundations for the final conclusions and recommendations.

4. Analysis

4.1 General results

Figure 6 illustrates the aggregate scores of the seven participants for the different options. The individual rankings can be found in Appendix V. As can be observed in Figure 6, there are a total of 11 options. Next to the eight core options, three participants have proposed an additional option: *genetic editing*, *restructuring biomass* and *vaccines*. All core options were assessed by all seven participants except for functional feeds and selective breeding which were assessed by five participants. This was due to a lack of knowledge or not perceiving them as a valid option. Additional options have only been scored by the respective participant, which is why no extrema (blue lines) can be observed for these options. The symbol after the 'Cleaner fish' option indicates that this option has been ruled out by at least one participant.

There is quite a lot of variation in the scoring, most options are both scored on the low and on the high end of the spectrum. Selective breeding clearly seems to stand out in a positive way. It has not been scored lower than 60 and averages on the very high end of the spectrum.

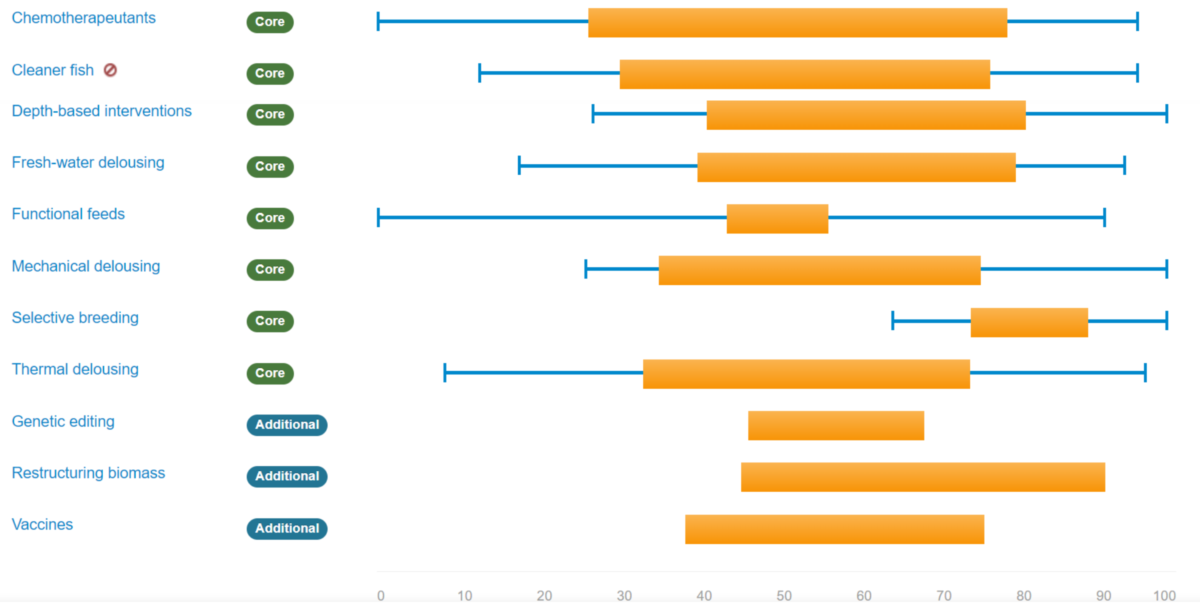

Figure 6. General overview of the average scores on all criteria for both core and additional options. The chart shows both rank extrema (blue lines) and rank means (orange bar). The rank extrema data gives a full picture of the variability in the ranks assigned by different participants. The rank means give an indication of the distribution of participants' ranks within the ranges defined by the extrema.

4.2 Perspectives, issues and clusters

4.2.1 Perspectives

Perspectives are groupings of participants. Since most participants have a background that is quite diverse, dividing participants into perspectives and comparing the data for different perspectives would not yield trustworthy results.

4.2.2 Issues

Participants were asked what criteria they wanted to use to appraise the options. It became clear that a few criteria were deemed most important. These are criteria related to *effectiveness* (6), *welfare of the farmed salmon* (6), *cost* (4), *environmental impact* (4) and *availability* (4), for which the number corresponds with the number of participants that proposed them. As can be observed, cost-benefit is grouped both under effectiveness and *cost*. Issues will be covered more in-depth in the following sections. Next to that, *dependency on the environment* (2), *resistance* (2), *ethics* (1), *regulatory barriers* (1), *size of the fish* (1) and *speed* (1) were also mentioned. One criterion of principle was proposed, which is *legality*.

4.2.3 Clusters

Clusters are groupings of options. Based on the results of the interviews, one cluster can be generated, consisting of: *mechanical, fresh-water and thermal delousing*. When scoring the options, these treatments were often covered simultaneously. This is because these treatments are similar in a lot of ways. During all of these treatments, salmon is pumped through a system on a well-boat. On this well-boat, they are bathed in freshwater or warm water or pressurized water and/or brushes are used to remove the lice in a more mechanical way. Combining these treatments on the well-boat is also very common.

4.3 Uncertainty

Again, the blue lines are indicative for the extrema and the orange lines for the means. The blue line shows the range of uncertainties, with the end of the blue lines showing the high and low extrema. More information about the calculations can be found in section 3.2.7.5 and Appendix IV. As can be observed in figure 7, there is a higher range of uncertainty expressed for *chemotherapeutants* than for *cleaner fish*. The orange line shows the average degree of uncertainty. The average degree of uncertainty for thermal delousing is higher than for *selective breeding*.

In general, the greatest uncertainties were expressed in the scoring of chemotherapeutants, with an extrema length of 171.67, followed by fresh-water (127.23) and thermal delousing (121.36). Selective breeding and *functional feeds* showed the least amount of uncertainty.

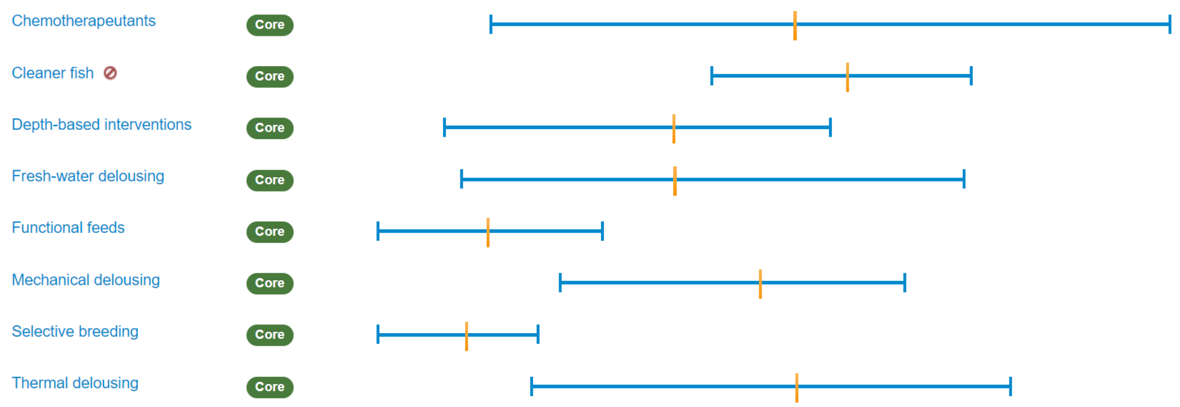

Figure 7: Uncertainty chart

4.4 Ambiguity

These charts express the relative degrees of disagreement over scores and ranks assigned by different participants. The orange bar shows the mean average degree of ambiguity. The blue line shows the range of ambiguity between extreme scores expressed by respondents. Again, more information about the calculations can be found in section 3.2.7.5 and Appendix IV.

Functional feeds and selective breeding were scored by 5 out of the 7 participants, which naturally results in less ambiguity between participants' scores and are therefore hard to compare to the other options in terms of ambiguity. As can be observed in Figure 8, participants scored *depth-based interventions* more similarly than chemotherapeutants, both in terms of means (52.49 vs 39.88) and extremes (73.18 vs 96.45). The main observation here is that chemotherapeutants and cleaner fish are the options of which most disagreement exists, being the ones with the highest average degree of ambiguity. The other options score fairly similar in terms of mean ambiguity.

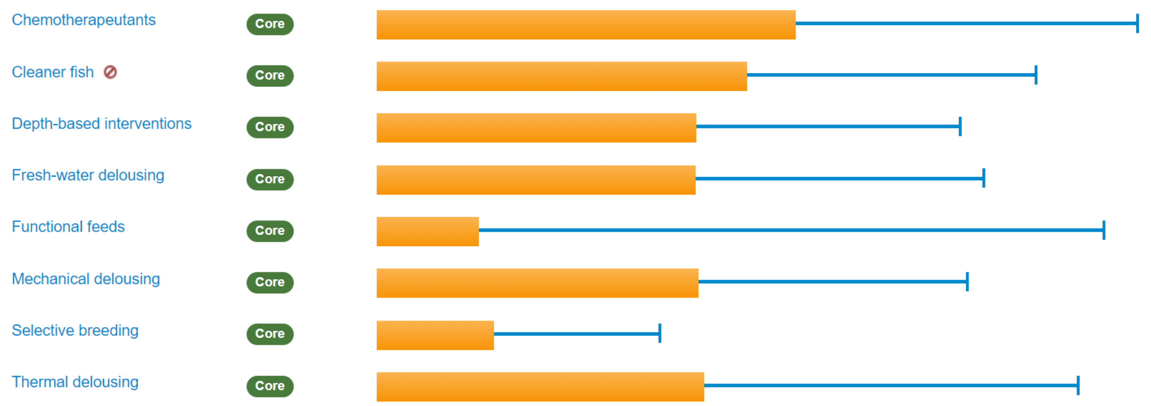

Figure 8: Ambiguity chart

4.5 Weightings

Figure 9 displays the weights that were assigned to the criteria. Section 3.2.7.5. and Appendix IV elaborates more on the calculations. Again, the blue lines are indicative for the extrema and the orange lines for the means. The issues (effectiveness, welfare of the farmed salmon, cost, availability and environmental impact) are the most relevant issues to be looked at. Welfare of the farmed salmon is perceived as the most relevant issue with a mean of 32.15, closely followed by effectiveness (29.51). Availability, with a mean of 25.55 is the third most relevant factor, closely followed by environmental impact (23.73). *Cost* is perceived as the least relevant factor with a mean of 16.74.

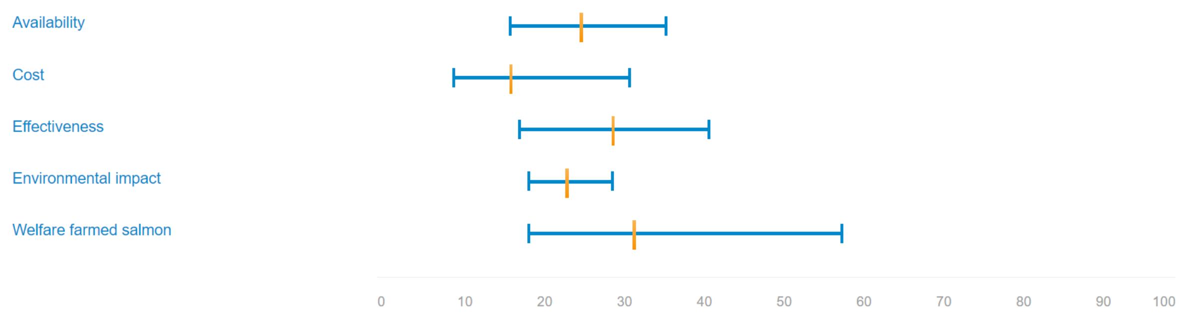

Figure 9: Division of weights assigned to criteria

Another way to perceive relevance is to look at the number of times a certain issue was mentioned. Table 1 displays how many times a certain criterion has been mentioned by the respective participant. The keywords used can be found in Appendix VI. This was 254 for *effectiveness*, 232 for welfare of the farmed salmon, 152 for environmental impact, 132 for *cost* and 86 for availability. This does partly match with the results in figure 9. Effectiveness and welfare of the farmed salmon are in both cases clearly the most relevant factors. Furthermore, environmental impact is somewhere in the middle for both. *Cost* is perceived as one of the least important factors, especially in the weighting stage. Only availability deviates significantly from the weighting stage, being mentioned just 86 times during the interviews. This can, however, also be explained by the fact that one participant assessed two criteria related to availability: availability of personnel and equipment.

Table 1: Criteria proposed by all participants, grouped into issues (*PE: personnel, EQ: equipment, SP: Speed, RF: Regulatory Framework, ET: Ethics, LE: Legality, SF: Size of the fish*)

Participant	**A**	**B**	**C**	**D**	**F**	**G**	**H**	**Total**
Effectiveness	63	59	28	14	48	42	x	254
Welfare of the farmed salmon	56	38	34	x	51	39	14	232
Environmental impact	36	76	22	18	x	x	x	152
Cost	44	45	x	9	x	34	x	132
Availability	24	x	x	x	x	34	PE: 14 EQ: 14	86
Dependency on environmental conditions	x	x	x	10	x	x	16	26
Resistance	x	6	x	x	x	x	9	15
	x	x	SP: 17	RF: 18	LE: 13	SF: 26	x	
Other	x	x	x	ET: 10	x	x	x	84

4.6 Results per issue

4.6.1 Effectiveness

As can be seen in figure 10, most of the core options were seen as relatively effective methods, as indicated by the means (orange bars). Only cleaner fish stands out because the mean on the pessimistic side is fairly low. This is due to the fact that some of the participants do not think that *cleaner fish* is effective at all. Participant A mentioned: "*For cleaning fish I think it's correct to have 0 because we see firms that have no effect at all.*" Participant G mentioned that it can vary a lot, also depending on the size of the fish: "*Cleaner fish cost-benefit, it can be from really bad to really good. So it can be from about zero because the fish was too big and you are not getting anything, to an optimistic of probably up towards 85.*" Vaccines was also scored on the lower side of the spectrum, but also got a fairly optimistic score.

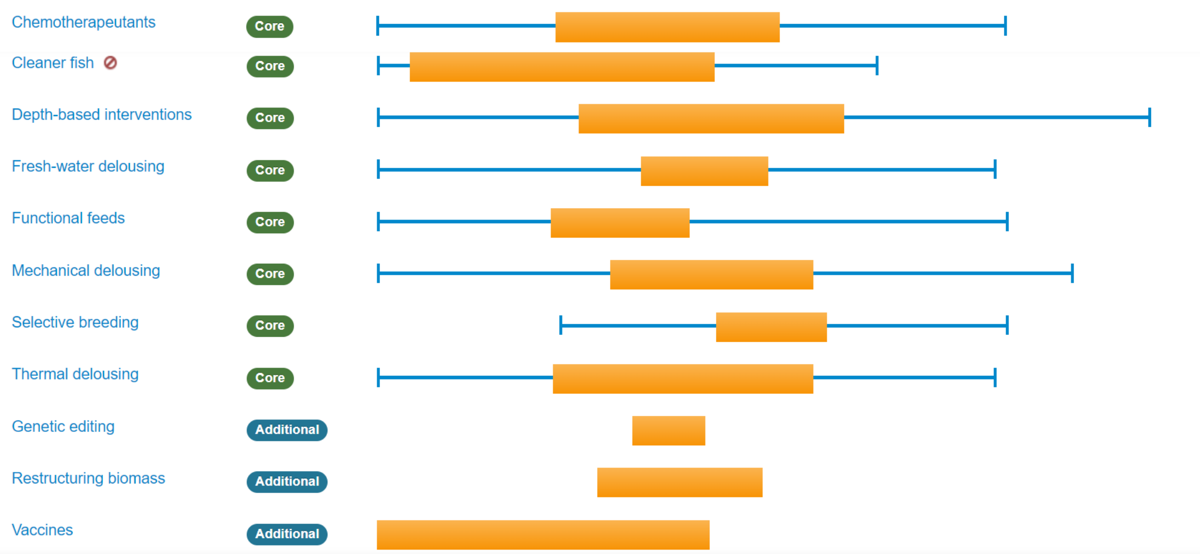

Figure 10: Rankings for effectiveness

4.6.2 Welfare of the farmed salmon

As can be observed in figure 11, again, there is a wide range of scores in terms of welfare for the farmed salmon. Most of the options have been assigned scores on both the very low end and the very high end of the spectrum. Mechanical and thermal delousing stand out in a negative way, receiving scoring on the lower end of the spectrum. Participants have emphasized the risk that these methods bring to welfare of the farmed salmon. Participant B mentioned: "*It has a high impact on the farmed salmon. I just read the fish health report of the veterinary institute and they wrote that 79% of the fish have mechanical wounds on the skin in the weeks after mechanical treatment.*" Participant B said the following about thermal delousing, in terms of welfare of the farmed salmon: "*Thermal delousing is quite similar to mechanical delousing. I think that is a method that is being discussed a lot in Norway. The food and safety authority suggested to ban it even last year.*"

Clearly, *functional feeds* and selective breeding are the best performing options with regard to welfare of the salmon, followed by restructuring biomass. It is not by coincidence that these are all preventative methods. Participant B mentioned the following about restructuring biomass: “*If you put the fish on sites with lower infection pressure you can protect the fish from all these treatments. So this should be really good for the impact on farmed salmon.”* Regarding functional feeds and selective breeding, participant G mentioned that it should only be beneficial to the wellbeing of the farmed salmon: “*If they eat the feed, they will only gain from it.”*

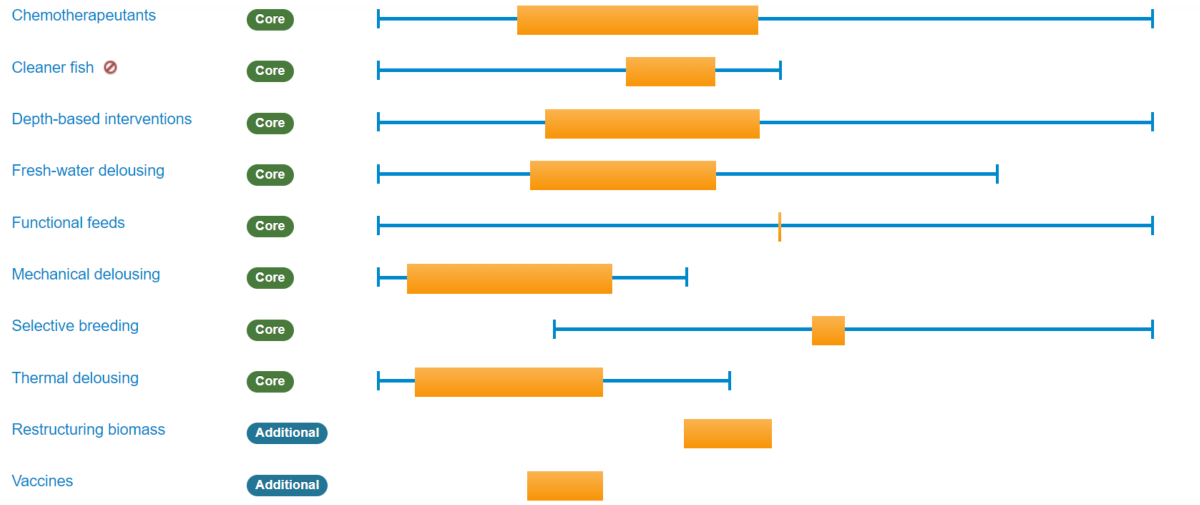

Figure 11: Rankings for welfare of the farmed salmon

4.6.3 Cost

Due to uncertainty, most of the options have been assigned scores on both the very low end and the very high end of the spectrum. In general, massive amounts of money are invested into solving the sea lice problem. As participant G mentioned: “*Delousing for one big farm can very quickly come to 100,000-250,000 euros.”* Participant D mentioned that chemicals and functional feeds are considered relatively cheap options: “*Maybe the least expensive would be the chemicals and functional feeds, they are super expensive, but maybe less so than others.”* On the other side of the spectrum stands genetic editing, as participant D mentioned: “*Gene editing is probably the most expensive, because you need to develop pretty much a vaccine or something, resistance. That is just so much R&D. So I think that would be most expensive.”* Regarding the exact costs of selective breeding, the opinions vary. Participant D mentioned: “*Selective breeding is difficult, you need facilities and cost is high so 20-40 maybe.”* Participant G mentioned: “*When you get good breeding lines, you get incredible cost benefit improvement, on disease, on growth, etc.”* Thus, the benefits should be able to easily outweigh the costs.

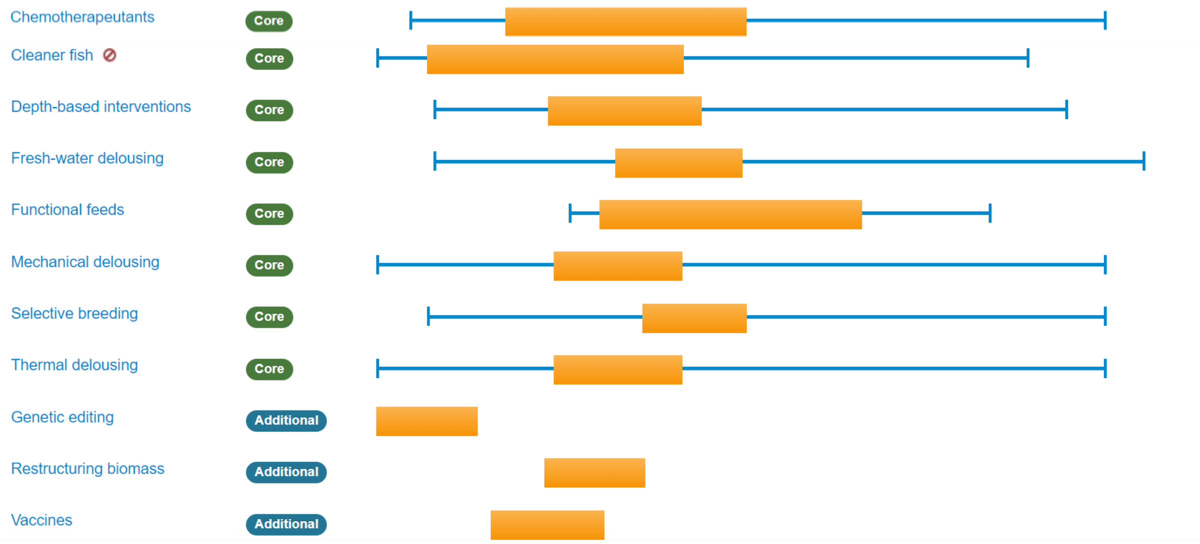

Figure 12: Rankings for cost

4.6.4 Availability

The issue of availability includes both availability of personnel and availability of equipment. Clearly standing out is vaccines, which scored very low due to the fact that currently, none is available. Functional feeds, on the other hand, has a high availability. Participant G mentioned: "*I would say that functional feeds are always available, because we have ridiculously good logistics and very good contact between feed company and the farmer.*" Selective breeding should be available to anyone considering salmon eggs are widely distributed. Participant A mentioned: "*Availability of selected strains for sea lice resistance, or sea lice tolerance is good here today as far as I know.*"

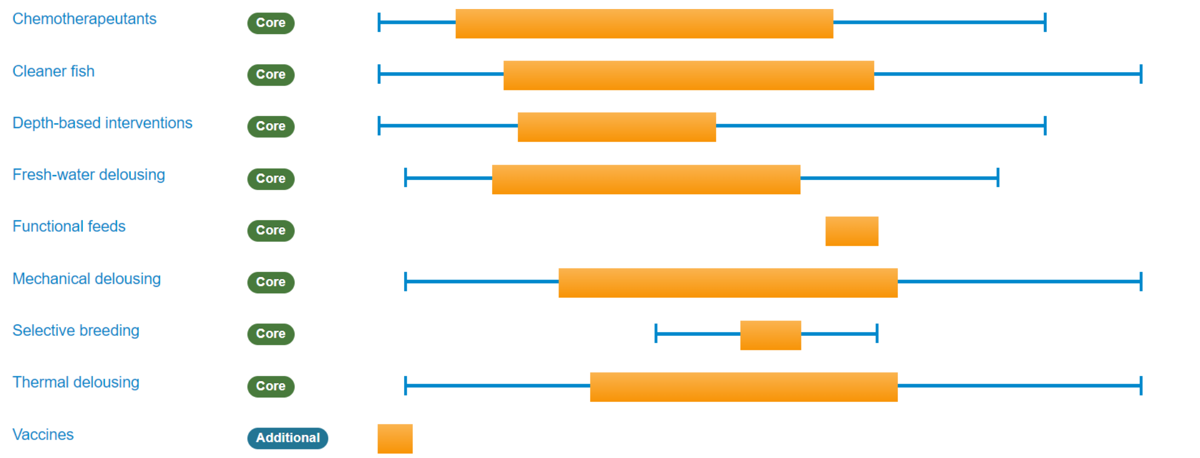

Figure 13: Rankings for availability

4.6.5 Environmental impact

In general, most of the methods do not affect the environment a lot. The biggest potential environmental impact can be observed for restructuring the biomass, as participant B mentioned: *"Maybe the site you're moving the fish to, have these corals on the bottom or as an example, and as you know, the pollution from the sites or the farms is not included in the regulatory system for biomass. It's only the sea lice."* Next to that, functional feeds and chemotherapeutants can be spread in the environment and thereby affect other species.

Cleaner fish, in this case, seen as part of the environment, is also affected massively, considering 40 million die each year.

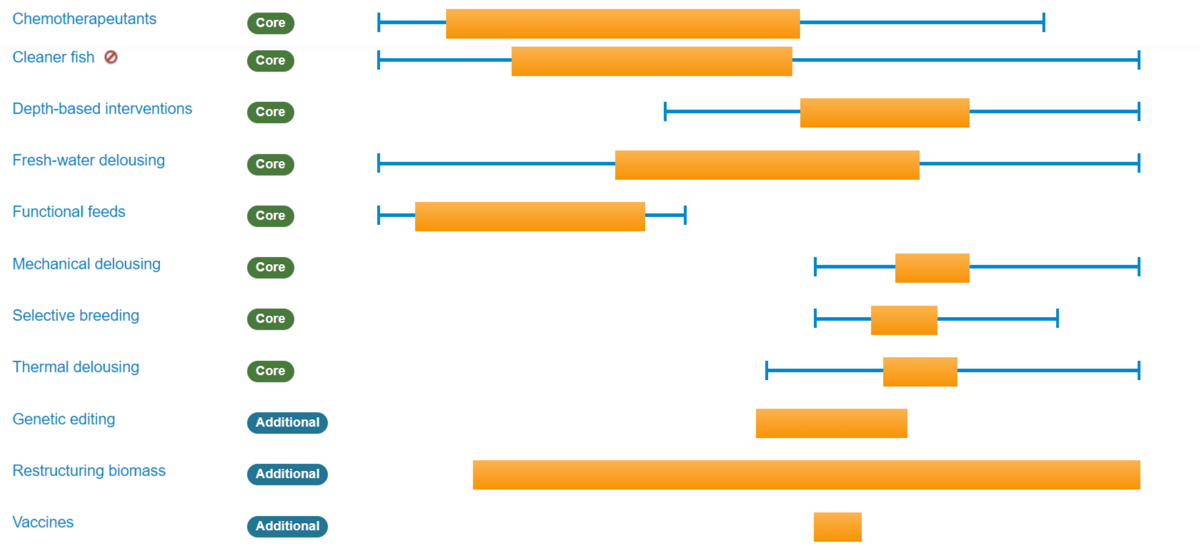

Figure 14: Rankings for environmental impact

4.7 Results per option

Generally, the list of core options that was presented to the participants was deemed comprehensive. Three participants added an extra option to the initial list. The participants were familiar with most of the options, but some needed clarification, as to what was exactly understood under a certain term. Depth-based interventions can, for example, cover more methods than the two initially described methods (snorkel cages and lice skirts). Another remark was that some options could be more detailed and a distinction should be made between different types of these treatments during the scoring process. There is a wide variety of chemotherapeutants, mechanical treatments and depth-based interventions that have their own advantages and disadvantages. This, in turn, also influences the scores that would be assigned to them.

4.7.1 Chemotherapeutants

As can be observed in Figure 6, the scores for chemicals are extremely dispersed. Generally, chemicals are perceived as both a very good and a very poor-performing option. A distinction has to be made between bath treatment and in-feed treatment chemicals. In the latter, for example, no handling is involved, which means that the salmon are less affected by the treatment. However, generally, chemotherapeutants score quite well in terms of salmon wellbeing.

Chemotherapeutants have also proven to be relatively effective. Throughout the history of salmon farming, it is one of the most used delousing methods. However, the effectiveness has decreased dramatically over the years, as the lice have become resistant to some of the chemicals. It is therefore recommended to use different types of chemicals, to reduce the risk of lice developing resistance.

Chemotherapeutants are not expensive compared to most other methods, solely looking at the cost of the chemicals. Looking at the delousing operation as a whole, additional costs have to be considered as well. Starving the fish before you handle it, for example, means losing 2-4 days of growth and the handling itself will also result in some mortality, which means less profit.

The use of chemotherapeutants can be very damaging to the environment, as they can affect and even kill species living in the surrounding ecosystem. Participant D mentioned: "*They use shell softening agents that will affect the lobster and other species.*" Participant B mentioned that the actual impact is dependent on several factors: *"In some areas where the current is favorable and stuff and if this is diluted effectively and also dependent on which GMO therapeutics you use, some are more environmentally friendly than others."*

On the other hand, the effectiveness of chemotherapeutants is also dependent on the environment. For the use of hydrogen peroxide, high salinity and low temperature are the most ideal water conditions for effective treatment. Chemotherapeutants are easily available and affordable to almost everybody working in salmon farming. They are stored throughout all of Norway.

4.7.2 Mechanical, fresh-water and thermal delousing

As mentioned before, these delousing methods are very similar and the combined results will be discussed jointly in this section. The results showed that, on average, freshwater delousing is perceived as the most promising option, followed by mechanical and thermal delousing.

Thermal delousing can be harmful to the fish, causing damage to the fins due to panic reactions and even possible brain damage due to stress. Mechanical delousing can be even worse in terms of fish wellbeing, as a lot of fish die after being handled. However, this is more dependent on the way the fish are handled than the actual treatment, which is emphasized by participant A: "*If the operation is done with not optimized technology and or not skilled or engaged personnel you can do lots of damage.*" Participant G described how the robustness of the fish should be taken into account when applying these methods: *"If you apply mechanical or thermal delousing on fish that are physically weak, it can be extremely damaging to the fish."* According to one of the participants, the food and safety authority even suggested banning these methods because of the stress that they cause to the fish. Unlike thermal and mechanical treatment, freshwater is relatively animal friendly. Salmon need to be resistant to freshwater since they naturally swim up and down the rivers for mating purposes, which means that bathing them in freshwater will not harm them too much.

The environment is hardly affected by these types of treatments. Some indirect effects like the energy that is used by the wellboat can affect the environment slightly, but there are no major risks. Electrifying these boats could reduce this impact even more. Thermal treatment requires heating of the water, which is another small energy expenditure.

These options are very popular amongst farmers due to the fact that they can be used for immediate sea lice removal. However, they are only short-term solutions. Apart from chemicals, mechanical and thermal delousing are the most used methods in Norway. They can be a very effective way to remove lice from the salmon, but can also be relatively inefficient if not used in the right way. Participant B mentioned that: "*It does not seem like a very effective method, because they have to repeat it up to 10-12-15 times in one production cycle.*" Thermal and freshwater delousing are both also perceived as effective methods. What goes for all these treatments, is that the effectiveness is dependent on the length and frequency of the treatments and on the skills of the farmers.

Thermal and mechanical delousing can be quite expensive. Not only the operation itself but also losing fish due to the treatment can result in a lot of costs for the farmers. The mortality numbers for freshwater treatments are lower, which makes it a cheaper method. Freshwater has to be transported to the location, which is an additional cost for that treatment, but overall freshwater delousing is still cheaper than thermal and mechanical delousing.

There is a risk that lice can develop resistance to lower salinities. In this case, the freshwater treatment could become completely obsolete. The same goes for thermal treatment, which could select for lice that are resistant to warmer temperatures. Mechanical delousing could select for lice that are better attached to the salmon, but this is not believed to be a big risk.

Since all of these treatments are done on a wellboat, it is crucial that farmers either have a wellboat themselves or access to the services of a wellboat. The capacity for these treatments has been built up heavily over the last few years. As opposed to thermal and mechanical treatments that have all required elements on board, freshwater treatment requires fresh water to be transported to the wellboat. Therefore, freshwater treatment has some limitations in terms of accessibility.

4.7.3 Cleaner fish

The use of cleaner fish is generally not believed to be a solution that can completely solve the sea lice problem by itself. It is more used as a side measure, that is continuously going to get rid of part of the lice and which can prolong the time until an intervention is needed with other more immediate measures such as mechanical or chemical delousing. As participant A mentioned: "*If you prolong the intervention time one or two or three months, that is very valuable."* However, the way in which cleaner fish are used right now is not very efficient and more research needs to be done on the biological needs of the cleaner fish.

Also, an important distinction has to be made here between two types of cleaner fish: the ballan wrasse and the lumpfish. Both of these species can be produced or wild-caught. Lumpfish are easy to farm, which means that the dependency on wild catch is low. Wrasse is more difficult to farm, which makes farmers very dependent on the wild catch.

It has to be mentioned that cleaner fish has been ruled out by one of the participants because it is considered an illegal option. The legality has been a point of discussion with other participants. This is mainly due to the fact that the way cleaner fish are used is perceived as unethical. 100% of the cleaner fish die for the sake of delousing. Participant B pointed out that the way cleaner fish are not treated as they are supposed to: "*The lump fishes are really susceptible to several pathogens and diseases and there is no veterinary treatment for these fish. They are getting sick and they are protected in the Norwegian law like other rare animals, but they are not getting any protection at all."* On top of that, the cleaner fish can not be used for food consumption and are therefore wasted on the farms, especially when their effectiveness seems to be lacking.

The use of cleaner fish poses almost no risks to the welfare of the salmon, it was perceived as the least harmful out of all of the options. However, the effectiveness of the cleaner fish is debatable, some people do not see it having any effect at all. The effectiveness of the cleaner fish was scored in a very wide range. One of the reasons is that the effectiveness will vary from place to place. It is important to take good care of the cleaner fish, participant F mentioned: "*You need to make sure that the cleaner fish are fed and that it has its own area in the pen where it can hide for instance."* Furthermore, the effectiveness of the cleaner fish depends on the size of the salmon. If the salmon is too big, the cleaner fish can not keep up with the speed of the salmon to eat the lice and, in the worst case, even be eaten by the salmon.

The use of cleaner fish poses several risks to the environment. By removing the fish from their natural environment, the natural stocks of cleaner fish are eradicated and the local ecosystem can be heavily affected. In turn, the cleaner fish can also negatively affect the new environment, especially when escaping. On top of that, transporting the cleaner fish to the farms accounts for a significant amount of energy pollution.

There is some risk of developing resistance towards lice by using cleaner fish. The most colored lice are the easiest prey for the cleaner fish, which means that less pigmented lice could eventually evolve to avoid being eaten by the fish. So far, this theory has not been supported by documentation yet.

The supply of cleaner fish is fairly good. Lumpfish are easier to produce than ballan wrasse, but even for the production of wrasse improvements have been made over the last few years. This also translates back to the costs, which are significantly higher for wrasse than for lumpfish. Compared to the other methods, cleaner fish can be seen as a relatively cheap way of delousing. However, when looking at the cost-benefit relation, cleaner fish can be quite costly, considering they need to be rebought every time they die and might not even be that effective as a delousing measure in most cases.

4.7.4 Depth-based interventions

Next to the snorkel and skirt cages, participants discussed a couple of other depth-based interventions such as submerged cages and closed and semi-closed containments, which are thought to have huge potential. Nevertheless, before these new technologies are implemented on a large scale, research needs to be done to validate these methods in terms of effectiveness, fish welfare and other variables in the long term.

A big advantage of depth-based interventions is that you do not need to handle the fish. With these technologies, salmon can be produced without any direct impacts. A downside is that when pathogens get in these semi-containments, it is very difficult to get them out again. The reduced water quality can be a threat to the salmon living inside. Therefore, farmers need to be well aware of the environmental conditions of the location they are placing their depth-based technologies in.

This is also closely related to the actual effectiveness of the technology. Participant A mentioned that: "*Some actually increase the risk of getting lice on the fish and others do it very well and get almost no lice through a whole production cycle."* On average, depth-based interventions was the highest-scoring option. As mentioned, there are different types of depth-based interventions and the effectiveness also varies amongst them. Closed, semi-closed and submerged cages are believed to be very effective against lice, whereas skirts have proven to be less effective so far. Skirts can also pose oxygen problems during the period with the hottest water. Therefore, managing these technologies well is crucial for achieving good results in terms of effectiveness and fish welfare.

Initial investments for depth-based interventions will be high because it costs a lot to produce and build these structures. There are also some operational costs involved with this technology. These high initial costs could be a problem, but the expectation is that this investment will easily pay off in the long run, since it is a long-term investment that can be used for more than one generation. This is also one of the major advantages of the technologies, it should be a long-term solution to the lice problem.

4.7.5 Functional feeds

Functional feeds have not been assessed by all participants because of a lack of knowledge about this option. The participants that did assess functional feeds also seemed to be hesitant about expressing their opinions and their assessments varied a lot. Thus, there seems to be a lot of uncertainty about using feeds as an effective delousing method. The connection between in feed chemotherapeutants and functional feeds has also been made by a couple of participants. This means that it is not always clear what functional feeds actually entail. Furthermore, like with cleaner fish, functional feeds are perceived as a 'side measure', used to get rid of a small portion of the lice. It is an immediate measure that can prolong the time between other treatments.

The welfare of the salmon does not seem to be threatened by eating functional feeds. It is specifically designed to only improve the health of the salmon to be able to withstand sea lice without interfering with the regular functioning of the salmon. However, functional feeds can affect the environment in a negative way. When functional feeds are thrown in the farms excessively, they can be eaten by other species and impact them in this way.

The participants scored the effectiveness low, but documentation about the actual effectiveness of functional feeds seems to be lacking. Also, unlike pharmaceuticals, functional feeds do not have to be tested extensively before they can be sold. One of the participants stated that he/she would therefore never trust it. However, participant G described how functional feeds can be crucial for other diseases such as pancreatic disease: "*If the fish is a little bit on the wonky side, some of the functional feeds can be absolutely important to improve their health and reduce both disease and not lose a lot of fish, because fish will regrow the pancreatic tissue given time."*

The functional feeds are very easy and quick to implement, as it is only a matter of replacing the original feed with the 'functional' one. On top of that, they are relatively cheap and easily accessible to any farmer. The logistics in Norway are good enough to supply almost anyone in time. However, when the feeding is done excessively, a lot of feed might be wasted which is not cost-efficient.

4.7.6 Selective breeding

As with functional feeds, this option has been left out by some of the participants due to a lack of knowledge. Selective breeding seems to be underdeveloped compared to other options. However, it also seems to have a lot of potential according to some of the participants. Participant G mentioned: *"I have huge faith in selective breeding".* As can be seen in figure 6, selective breeding scores the highest on average.

In terms of health for both the salmon, other species and the environment as a whole, selective breeding can be a promising solution. It does not seem to be associated with any negative externalities. It has to be mentioned, though, that selective breeding comes with some risks for the salmon. Participant G mentioned: "*You can completely ruin the fish if you push it outside its environmental tolerances."*

Selective breeding takes a lot of time, which is of course a big downside for this option. For current lice outbreaks, selective breeding will not be of much help. On the other hand, if it works properly, it will also be a permanent solution to the sea lice problem. If the fish can be bred in a way that makes them grow faster, the time in the sea is reduced and the risk of lice is reduced. Next to that, if the resistance toward sea lice is increased, the pressure is also reduced. Not everyone is convinced, however, that selective breeding will result in completely lice-resistant salmon. Participant F said: *I do not think that you will get a 100% lice-resistant fish. But I think if you can explore the possibilities there, you can get some resistance and it will be helpful, but it takes time.*

Next to the amount of time it takes to do research for selective breeding, the costs can prove to be a barrier. Like with depth-based interventions, the initial costs are high but will most likely pay off in the long term. Once a selective breeding program toward sea lice-resistant salmon has succeeded, accessibility to these fish should not be a problem. Anyone should be able to get their fish in large quantities.

4.7.7 Genetic editing

Genetic editing was proposed as an additional option by participant D. It was described as: *"Altering the genome of the Atlantic salmon to resist salmon lice, through for example CRISPR"*. This option is more on the radical and long-term side, but is believed to potentially be one of the ways to completely solve the lice problem.

As mentioned, this option when executed successfully could be able to be a permanent solution to the lice problem. In theory, once the DNA is altered in a way that it can allow salmon to be resistant to lice, the problem is solved. In terms of negative externalities, the participant is not too worried about negative side effects.

With regard to cost, genetic editing is considered the most expensive option. Much R&D is needed to alter the DNA in a way that it can be resistant to lice. Also, the development of these genes is extremely complicated and might take loads of time. These are massive barriers that have to be overcome before genetic editing can be a viable solution.

4.7.8 Restructuring biomass

Another option that was proposed by one of the participants is to restructure the biomass. It is described as reducing the biomass and restructuring the biomass sites in the production areas. Participant B described: *"Our organization sees that the fish farming industry has grown way beyond environmental sustainable limits."* This solution is a completely different approach than the core options. This solution tackles the problems that lay at the roots of the sea lice problem: the high density of fish on farms and the location of the farms. By lowering the density of fish, the risk of diseases spreading like sea lice can be lowered significantly. By relocating farm sites to sites that are less vulnerable to lice, lice outbreaks can also be reduced.

This approach could be very effective. The results of the report of the veterinary institute showed that restructuring the biomass in a certain production area could result in a lice reduction of 30%. This does not take into account the effect of reducing the biomass in that area, which will in turn also be reducing the number of sea lice significantly.

4.7.9 Vaccines

Another participant proposed the development of a vaccine as an additional option. This vaccine should either give the salmon the ability to withstand the sea lice or give the salmon some traits that prevent the lice from developing viable larvae. Either the immune system or the salmon kills the newly attached lice or the lice develop on the salmon without having the ability to reproduce.

In terms of fish welfare, the vaccine is seen as a promising method. The fish wouldn't have to be handled more than they are handled right now, because the vaccine against sea lice can be given simultaneously with the vaccines that are already given for other diseases. If it can be given in-feed, there would even be no negative welfare effects at all.

In terms of sea lice removal, the vaccine has the potential to be very effective. However, there is not a well-functioning vaccine on the market currently. Therefore, the availability is also questionable. With regard to environmental impact, the vaccine is not expected to pose any risks. When it comes to risks of resistance, however, the vaccine might be susceptible to adaptation or development of resistance by the lice. Finally, the costs of vaccinating salmon would not be very high, as this can be done together with vaccination against other bacteria and viral diseases.

4.8 Proposed solutions

After the standard MCM process, the participants were asked about their thoughts on the problem as a whole and if they had a certain vision in mind on how to solve it by, for example, combining certain methods. This allowed participants to bring up more 'out-of-the-box' solutions and give them some more room to express any thoughts left on the issue. The way in which the participants answered these questions varied significantly. Some of the participants had a clear vision and others were hesitant about expressing thoughts. This explains the variety in the amounts of text below.

Participant A

Chemotherapeutants can be very effective for deactivating all stages of lice. When they are used early spring, before the temperature rises, the development of lice in the whole area can be retarded. It is recommended to use the same chemotherapeutants only once during a production cycle though, to prevent the development of resistant lice but also to reduce the risk of negative environmental impact. The most effective way to reduce the number of lice is also dependent on the site and the dynamics in the area (e.g. connections between farms). It would be helpful to define criteria for when to use certain methods. Real-time data of sea lice numbers and environmental data could be of great help when used correctly. By accumulating and averaging data of the individual fishes per cage and per farm, a lot of information is lost in the process. Combined with environmental data of temperature and salinity, this information could give more insights into genetic selection for example.

Participant B

A shift needs to happen away from short-term measures like thermal and mechanical delousing, which are bad for the welfare of the salmon, to a more structural solution. Restructuring biomass, by reducing the amount of fish in open pens and relocating the farm sites could be a good structural way to gain control over the sea lice, especially in high-pressure areas. This, in combination with closed and semi-closed containments, can be a very effective solution for the sea lice problem.

Participant C

Thermal and mechanical delousing could be used together to get rid of more lice. Mechanical treatment can be used to remove the bigger lice and thermal treatment can target the smaller stages of lice.

Participant D
Gene editing could potentially solve the whole sea lice problem. By altering the genome through CRISPR, the salmon can become resistant to sea lice. A framework that allows for combining treatments could also make it easier to reduce the number of lice.

Participant E
In the long run, farmers need to move away from traditional open net-pen farming, because this has its limitations. New technologies, like depth-based interventions, are needed to isolate salmon from the lice in open pens. Placing cage technologies at strategic points along the coastline could bring down the infection pressure significantly. This could be done by removing sites that are in the middle of a network of infection or by replacing them with closed cages. Breeding salmon that are resistant to lice could also be very helpful and combined with other kinds of methods.

Participant F
Participant F was fairly convinced about the potential of selective breeding: ”*Actually, selective breeding is probably where I would put my biggest hoping into. Because that would be a very natural, generic way to improve the issues we are challenged, we are challenged with.”* The solution to the sea lice problem will most likely consist of a combination of treatment methods, farming technologies and better genetics. Which treatment or technology should be used is location-dependent. For sea lice-sensitive locations in fjords, closed systems might be used. Semi-closed systems might be more fitting to locations a bit further away from the sea. For offshore farms, completely open cages can be used without much sea lice pressure. Another way to reduce the sea lice pressure is to keep the younger salmon on land in recirculating systems, thus delaying the outset of transfer to sea with the risk of getting affected by sea lice. In the case that these strategies still allow for sea lice outbreaks, a combination of treatments (freshwater, thermal and chemical) can be used to target the lice in different ways. This can prevent the development of genetic resistance. Analytical models based on big data can improve our sea lice management skills. For example, by better understanding where lice are going, farmers can selectively protect a cage or site.

Participant G
A combination of different kinds of farms and treatments can be used to lower the number of sea lice on farms. With land-based farming, the lice problem can be completely avoided. Next to that, closed systems in the sea can reduce the sea lice levels down in the fjord. Mechanical delousing can be combined with freshwater and thermal delousing. After the freshwater treatment, salmon can be sent through for mechanical or thermal treatment on the wellboat. The chemotherapeutant hydrogen peroxide can be combined with ultrasound Functional feeds or snorkel cages/skirts can be used to prevent the larvae from attaching to the skin of the fish.

It can be concluded that the opinions about the future of dealing with sea lice vary a lot. The common denominator is that current practices are not effective and that radical change is necessary in order to tackle the issue. This can be done by doing structural adaptations such as developing criteria for the use of certain technologies and methods, restructuring the biomass, using big data and investing in radical technologies such as selective breeding and land-based farming.

4.9 Combining MCM and proposed solutions

The MCM process is designed for the participants to feel like they are in the driving seat and to be able to steer the conversation. The MCM process let participants evaluate the options that were found in the scientific literature on their self-constructed criteria (Coburn et al., 2019). As the initial list of options might have excluded promising options, the participants had the opportunity to add new options. This gave the participants plenty of space for input. However, since the sea lice problem might not be able to be solved by implementing one option, after the MCM interview, participants were asked if and how options could be combined. In addition, participants were asked to formulate their vision for solving the sea lice problem in order to give them more room to express themselves on the topic. This also allowed the participants to share more out-of-the-box solutions or solutions that might have been hard to include in the MCM assessment. These results were covered in the previous section. The next section covers drawing further conclusions, based on the results from the MCM interviews and the open-ended question asked afterward. Five take-aways are elaborated on.

4.9.1 There is no one-size-fits-all solution to the sea lice problem

Several participants have emphasized the importance of the farm sites with regard to sea lice. Generally stated, there are currently three categories: in-fjord sites, near-shore sites and off-shore sites. In-fjord sites are the most susceptible to sea lice. Near-shore sites are less susceptible to sea lice but still need proper sea lice management. Offshore sites pose little risk in terms of sea lice. These sites ask for different strategies. For in-fjord sites, closed systems could be implemented in order to diminish the risk of lice infestations. For near-shore farms, semi-closed systems could be a better way to keep the lice out while still having water flow through. Offshore farming can be done with open pen cages. Next to these categories, an additional category was proposed by multiple participants: land-based farming. This is seen as a way to avoid the whole sea lice problem. It is generally seen as a promising way to expand the limited production area by producing salmon in a place that is currently barely utilized. Nevertheless, it has its own implications. Norwegian waters are a public good, whereas land is possessed by different owners. Also, areas suitable for land-based farming are limited in Norway.

Furthermore, criteria should be developed to not only decide whether a location is suited for a certain cage technology, but also to decide on the delousing methods to be used. As previously mentioned, the natural environment is an important factor. Chemotherapeutants are most effective, for instance, when used in early spring, before the water temperature rises. Perhaps equally important are the dynamics between farms. If a farm is located in between several other cages or farms, it should be taken into consideration how methods can affect other farms. When there is no communication about sea lice outbreaks, the effects can be detrimental to neighboring farmers.

4.9.2 A few current delousing methods seem to be either unethical or ineffective

Some participants have explicitly stated to be against certain methods. The use of cleaner fish is by several participants considered an unethical delousing method. One participant mentioned that: These fish are supposed to be protected by Norwegian law, but in reality, they are all sacrificed for the 'greater good', which is delousing the salmon farms. This, in combination, with the debatable effectiveness makes it hard to see this as a viable option.

Other methods such as mechanical and thermal delousing are also considered to be not so animal friendly. These methods affect the salmon by stressing them and causing wounds to the fins and gills. Unlike the cleaner fish, these methods seem to be quite effective and used on a large scale. Hence, whether these methods should be used is debatable. It seems that, without a long-term solution, these kinds of methods will still be necessary in the following years to reduce sea lice pressure.

4.9.3 The financial cost of delousing methods is not the biggest barrier

The cost of delousing methods does not seem to be a major bottleneck. Although it was used by most of the participants as a criterion to assess the options, not much attention was given to this aspect. During the interview, it was mentioned 132 times, which was considerably less than for example effectiveness (254) and welfare of the farmed salmon (232). In the weighting stage, the cost was valued even lower, as clearly being the least important factor. Participant A has been very explicit about this: "*It (Economy) has to be included with. Because if you have the opportunity, and you have made all your choices and weighing between different methods, your last could be to choose the method giving best economy in short, or longer term."* Participant B has a similar take on the economic aspect: "*I would not like to weigh the economic criteria as high as the environmental impact and the welfare impact on farmed salmon."*

When asked if the methods were affordable to most farmers, participant D answered: "*Everything is affordable right now, because the salmon prices are very high. It is like 120 NOK per kilo and normal it is 60 NOK per kilo. They earn a lot of money right now."* Hence, as a result of the big profit margins, delousing methods are relatively cheap. Considering the benefits of delousing methods, farmers do not hold back when it comes to investing in them. According to one of the participants, delousing a big farm can cost 100,000-250,000 euros. This does not mean that cost is not important at all. Naturally, for the farmers themselves, which are profit-driven, costs are central to the business. With respect to deciding on a delousing method, however, they seem to be more focused on the actual effectiveness.

4.9.4 Data is key

A topic that has not received much attention during the interviews, but that was brought up by several participants, is the use of data. Regardless of which delousing method is used or should be used, data and data-sharing could play a crucial role in salmon farming. Since 2007, salmon farmers have been obligated to count and report the number of sea lice on their farms. The job of the NFSA is to supervise the aquaculture sector to ensure that the goals for salmon lice treatment are met. Barenswatch is an open access platform used to create an overview of the sea lice numbers, along with other data such as fish health and weather conditions. It is subject to the Ministry of Trade, Industry and Fisheries, and the Norwegian Coastal Administration leads the department (Barenswatch, 2022). This results in a self-regulating system in which farmers feel pressure to manage their sea lice numbers, due to the fact that they can be criticized by their neighboring farmers. The openness of the system is necessary for farmers to build trust, as also mentioned by participant F: "*I think if we are to have any kind of trust in our communities, we will build a trust on the back of openness."*

A downside of the current system is that all data is aggregated, which results in a loss of important information about salmon individuals. Together with the use of real-time data and additional background data, a lot of new knowledge could be generated. Participant A emphasized possible opportunities for implementing a new system like this: "*We will, for instance, see the variation in lice numbers per fish in a cage or in a farm and that could tell you something about the effect of genetic selection, for instance."* Therefore, a way to improve the current system is to try to get more out of the data that is collected.

What is more, investments in new technologies and models for collecting and processing data could be a great way to support this. Numerous companies are already investing in technologies such as automated sea lice counting, of which aquacloud is currently the largest one. These technologies and models can make the farms more manageable in terms of sea lice but also in more general terms. Participant F sees a bright future for data modeling: "*A lot of these improved technologies will not be necessarily mechanical equipment, they will be data models, they will be analytical models or methods and tools that we can use to improve our management skills and learning from what we're doing."* This, in combination with an adapted platform that allows for generating more individual data could improve sea lice management substantially. This conclusion is, however, based on the assumption that data privacy is not an issue. This should also be taken into account when looking at new ways of using data.

4.9.5 Focus on prevention, not on cure

It seems like salmon farms are in great need of a permanent, or at least long-term solution that minimizes the impact on the salmon and the environment. This can be achieved by shifting from a curative to a preventative approach. Generally, immediate strategies such as thermal delousing and chemotherapeutants can be seen as 'fire-fighting'. They are merely short-term solutions and also pose risks to salmon welfare and the environment. Depth-based interventions, selective breeding, genetic editing and land-based farming are preventative methods that could potentially lower sea lice pressure in the longer term. The latter two are centered around improving the resilience of the salmon towards sea lice and are therefore believed to be less vulnerable to the development of resistance by sea lice. If a salmon can either be bred or genetically modified in a way that they possess traits that make them resistant to lice, then the pressure of sea lice will be reduced significantly. Depth-based interventions is another potential way of reducing sea lice levels by having minimal impact on the salmon and the surrounding environment. Next to lice skirts and snorkel cages, submerged cages and semi-closed containment were proposed as depth-based interventions by participants as promising methods.

4.9.6 The role of the Norwegian Government is pivotal

Currently, the TLS is the main way through which the government tries to manage the sea lice problem. This system does, however, not seem to be the optimal way to govern the industry. It enables farmers to go for 'quick wins' by using immediate strategies to get rid of a lot of lice quickly. This is not a sustainable tactic. The result is that, instead of working towards a long-term solution, farmers strive to be just under unacceptable sea lice levels. This is typically done by using immediate strategies, such as mechanical methods and chemicals to get rid of lice quickly. These strategies are often either harmful to the salmon or to the surrounding environment. Therefore, the current traffic light system could benefit from some adjustments to make sure that the impact can be minimized in the long term.

Another option could be to implement a new regulatory system that is centered around solving the problem in the long term with structural changes. This can be done by educating the farmers about the earlier mentioned advantages for technologies and methods with regard to specific locations. As mentioned earlier, development of criteria tailored to specific site conditions can help the farmers in their effort to significantly lower sea lice pressure. Thus, by proposing criteria and offering expert advice, the farmers can be supported in a way that is beneficial to all. Next to education, the government could also look into a more financial system for governing the industry. Such a system could restrict the farmers that are using unsustainable methods that negatively affect the well-being of the fish or the environment by handing out fines. Furthermore, it could encourage farmers that want to implement sustainable methods by subsidizing them.

5. Conclusion and recommendations

This study had an explorative approach, which was to get a deeper understanding of the sea lice problem and potential ways to solve it. Methods for lowering sea lice levels were appraised by a number of stakeholders. Additionally, viewpoints about the problem as a whole and their vision of long-term solutions were collected. By combining these results, an attempt was made to answer the following research question:

What management strategy should be implemented in order to reduce the sea lice pressure on the Norwegian salmon industry?

The purpose of this study was not to provide one clear answer to this issue. It is a complex matter and subject to personal beliefs and with different valuation criteria. The assessment of alternative solutions did not yield one clear solution pathway to tackle sea lice in Norwegian salmon farming. Moreover, thinking in a one-size-fits-all solution is anyway a limited approach as it neglects specific local context conditions. Rather, the Norwegian salmon industry may be better served by a more holistic and to some extent differentiated approach to the sea lice problem.

Following the analysis, a number of recommendations can be articulated that may be important and helpful in further deliberation processes among stakeholders regarding the most optimal management strategy.

The first recommendation is to reassess whether some of the curative methods can be seen as ethically acceptable and whether or not these should be illegalized. Unfortunately, the industry is currently still dependent on curative methods that have major unwanted side effects. Also, immediate or curative strategies are great to achieve quick wins, but a long-term solution requires the implementation of other types of strategies. Thus, it would be better to focus on preventative methods such as depth-based interventions, selective breeding, genetic editing, restructuring biomass and land-based farming. It is recommended to do research on these kinds of preventative technologies. This can be done by the industry as well as the government or even collaborative efforts could arise. It can consist of local research by salmon farmers on specific locations and more fundamental research that requires large amounts of resources as with genetic editing.

A second recommendation is to focus on securing the quality of data that is collected on farms and focus on looking for more and better ways to utilize it. The system that is currently in place seems to waste valuable knowledge by aggregating data and could therefore be improved by inclusion of more individual data. Also, real-time sea lice counting could be used to generate valuable insights into sea lice behavior. Along with investments in new technologies and models for collecting and processing data, sea lice can become more manageable by, for instance, implementing automated processes.

Lastly, the recommendation to the Norwegian government is to assess the current policies and practices regarding sea lice management and salmon farming in general. The current governing system, which consists of the Traffic Light System (TLS) and Maximum Allowable Biomass (MAB) has proven to be relatively effective at lowering sea lice levels, but does not seem to be optimal for the long term. The Norwegian government could adjust its governing strategy by diversifying in a number of other areas. This can be done by looking into physically restructuring the salmon industry and developing criteria for the optimal technologies and methods to be used at certain locations. Also, as previously mentioned, reassessing whether some delousing methods are actually ethically acceptable can be a point of attention. These developments should preferably be done in consultation with other stakeholders, and the government needs to educate the industry about them afterward. To conclude, the government could be looking into a financial system in which farmers are either financially rewarded or punished when guidelines are not followed.

6. Discussion

6.1 Contributions

6.1.1 Substantive contributions

Considering the magnitude of the sea lice problem, remarkably little scientific research has been conducted. Most methods seem to be implemented by farmers in a hands-on manner. The research by Coates (et al., 2021) suggested that further research is necessary to identify strategy combinations that have antagonistic selective effects, in order to prevent lice from developing resistance. This study collects more knowledge about individual methods and possible combinations. Also, new strategies and technologies arose from this research, such as genetic editing and restructuring biomass, that were not yet discussed much in the scientific literature. Next to that, this study takes into account the governing side of sea lice management and provides insights into what underlying social structures or policies could streamline these strategies. In this way, it connects both the more technical side of sea lice management as well as the governing side. This can be seen as a substantive contribution.

6.1.2 Methodological contributions

The study has demonstrated a newly enhanced form of MCM, in which participants have more room to express themselves about the focal goal. Two things made this possible: the novelty of the method and the fact that the method is relatively open to interpretation of the process, features and results. While it is a mixed-method in nature, the numerical results are usually less important than the qualitative reasons (Coburn et al., 2019). The approach of this study was to make sure that the qualitative part of the method was even more the center of attention. Next to the arguments that were given to support claims made during the regular MCM process, additional insights were collected by ending with an open-ended question about the focal goal. This gives the participants a moment of reflection and allows for more out-of-the-box solutions and ideas that might be harder to come up with during the regular MCM process. One of the strengths of MCM is that it is a structured way of collecting information, but the pitfall might be that participants are thinking in a more one-dimensional way. Thus, ending with a more multi-interpretable question might result in gathering valuable insights next to the earlier collected information. These results can be combined to come to a more holistic narrative, as was done in this study.

6.1.3 Societal contributions

The societal contributions of this study go beyond Norwegian borders. As mentioned in the introduction, this study can be seen in the light of mainly two goals set by the UN (2015): ending world hunger (SDG 2) and conserving and sustainably using the oceans, seas and marine resources (SDG 14). The globally growing seafood industry is expected to contribute to the first goal (FAO, 2020). However, these developments need to be streamlined in a way that the second goal is also taken into account. Norwegian aquaculture, which is pioneering the seafood industry, could serve as a great example by focussing on both of these goals. Quintupling the value creation of aquaculture in 2050 should be done in a way that it considers the environment as well as the well-being of farmed salmon and economy, which are societal factors heavily affected by salmon practices. As has become clear from this research, several concerns exist about proper inclusion of these factors. By letting participants propose evaluative criteria and score them, it has revealed how certain methods are lacking in this aspect. Thus, this study explores how sea lice management can be done in a way that benefits the whole of society, and therefore adds significant value to it, both on a local, national and global level.

6.2 Limitations and further research

6.2.1 Limitations

A first limitation is the fact that most of the interviews were conducted remotely. Initially, the idea was to conduct all interviews vis-a-vis. It was, however, not clear beforehand where the target group would be exactly located. Bergen was chosen as a home base, being considered the headquarters of the Norwegian salmon industry, but it turned out that most participants were located in other parts of Norway. As a result, most interviews were conducted through video calls. Although this is not recommended, since the lack of face-to-face interaction might result in a loss of some qualitative aspects (Coburn et al., 2019), it also has its advantages. Participants were, in this way, able to search up and share some information online to support and clarify their claims.

Other limitations are concerned with the amount and the nature of the participants. Only 7 participants were interviewed, which cannot be seen to represent a statistically valid or otherwise representative sample. One of the strengths of MCM is that statistics and qualitative data are combined, but in this case, doing statistical analyses was not applicable. On top of that, some methods were only assessed by 5 out of 7 participants, which lowers the quantitative reliability even further. Also, the diversity of participants and their input might be affected by the sampling method of choice. MCM is aimed at incorporating a variety of perspectives, but the snowball sampling approach could have possibly led to results being a bit one-sided. This reduces the validity of the study.

Thirdly, it is debatable how reliable the results of the participants actually are. Some participants expressed that they were quite uncertain about assigning scores or making statements. Fortunately, the MCM exercise is specifically designed for including these kinds of uncertainties. On top of that, participants who expressed that they lacked knowledge for assessing a certain option had the option of skipping these.

6.2.2 Future Research

This study has attempted to bridge the gap mainly between the industry and governmental organizations by providing a technology assessment analysis that can support their deliberation process. It also points to the need of follow-up studies to dig deeper into both of these sides. Future research could build on the insights of this study by doing research on radical technologies that may provide long-term solutions as well as on constructing fitting policy measures and governance structures for sea lice management to manage these technologies.

Research could focus on the technological side of the issue and dig into radical methods with major potential such as genetic editing and land-based farming. These technologies are promising but it is essential that the actual effects are studied thoroughly and potential unwanted side effects are detected early on in the development. However, this needs to be done in accordance with the salmon farmers. It would be a waste of time and resources if it turned out that farmers are not in favor of a certain technology because it is too expensive or complex.

Next to the actual radical technology itself, a governance system that supports radical changes is also needed. Therefore, adequate research needs to be conducted on this issue. The same goes for more structural changes of the governing system such as with the TLS or platform for collecting and processing farm data. Development and implementation needs to be done in consultation with the farmers and other industry stakeholders in order to create a system that is beneficial to all: industry stakeholders as well as the natural environment.

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Appendix I: Stakeholders

Salmon farmers

- Leroy Seafood Group - Bergen - https://www.leroyseafood.com/en/
- Grieg Seafood - Bergen - https://griegseafood.com/
- Mowi - Bergen - https://mowi.com/
- Salmar - Bergen - https://www.salmar.no/en/
- Nova Sea - Lovund - https://novasea.no/en/
- Alsaker Fjordbruk - Onarheim - https://alsaker.no/
- Nordlaks - Stokmarknes - https://www.nordlaks.no/
- Sinkaberg Hansen - Rørvik - https://sinkaberghansen.no/english/
- Bremnes Seashore - Bremnes - https://www.seashore.no/en/
- Norway Royal Salmon - Trondheim - http://norwayroyalsalmon.com/en

Governmental institutions

- Innovation Norway (The Norwegian Government's most important instrument for innovation and development of Norwegian enterprises and industry. Innovation Norway supports companies in developing their competitive advantage and to enhance innovation.) https://www.innovasjonnorge.no/
- Center for Digital Life Norway (A unique transdisciplinary research center creating the biotechnology for tomorrow. They aim is to evolve new knowledge and methods to create value and address societal challenges.) https://digitallifenorway.org/gb/
- Norwegian Seafood Council (The Norwegian Seafood Council (NSC) aims to increase the value of Norwegian seafood resources. They do this through market insights, market development, market risk management and reputational risk management in select markets around the world.) https://en.seafood.no/
- The Norwegian Food and Safety Authority (A national governmental body, whose aim is to ensure that food and drinking water are as safe as possible for consumers and to contribute to a high level of plant, fish and animal health. They also contribute to ethical keeping of animals and encourage environmentally friendly production. In addition they regulate and control cosmetics and animal health personnel. Their broad expertise is employed to stimulate and improve their field.)
- The Research Council of Norway (Serves as the chief advisory body for the government authorities on research policy issues, and distributes roughly NOK nine billion to research and innovation activities each year. They work to promote international cooperation and increase participation in the EU framework program on research and innovation, and creates meeting places and provides a platform for dialogue between researchers, users of research and research funders.) https://www.forskningsradet.no/
- StartupLab (At StartupLab they empower ambitious founders on their earliest journey. As entrepreneurs themselves, they are 20 StartupLab team members all committed to increasing the likelihood of founder's success throughout the most challenging stage of their venture. By offering a unique work environment, with outstanding lab facilities, funding and a network of impactful investors, hard-won advice and tech savvy corporates – they have developed a new model to accelerate early stage startups.) https://startuplab.no/

- GCE Ocean Technology (an industry driven initiative for strengthening and internationalization of businesses, research and education. The cluster represents the world's most complete cluster for subsea life-of-field solutions. Their goal is to increase the cluster's competitiveness and global market share, and take a leading position in sustainable utilization of ocean resources.) https://www.gceocean.no/
- Maritime Bergen (a platform of cooperation for the maritime industry. They work towards development and sharing of knowledge, recruitment towards the industry, making the industry visible and enhancing the reputation.) https://www.maritimebergen.no/
- VIS (is the technology transfer office in Bergen. VIS works to develop innovation and commercialisation of research in the Bergen region. They are the regional center of expertise for innovation and commercialisation of research results.) https://www.visinnovasjon.no/
- SIVA (A public enterprise owned by the Norwegian Ministry of Trade and Fisheries, and facilitates innovation by building, owning and developing infrastructure for industry, startups and research environments. Siva develops knowledge and startup environments, and connect them to regional, national and international networks.) https://siva.no/
- Katapult Ocean (Invests in and supports startups with a positive impact on our ocean. They do this through their ocean impact accelerator, the Katapult Ocean fund and by creating a positive awareness of the great business opportunities in a sustainable ocean. 32 investments have been made in exciting ocean tech companies from all over the world (17 countries, 5 continents)) https://katapultocean.com/

R&D Institutions

- The University of Bergen (UiB) (Fisheries Ecology and Aquaculture research group) https://www.uib.no/en/rg/fea
- BI Norwegian Business School (An independent, not-for-profit foundation whose sole focus is education and research.) https://www.bi.no/
- Institute of Marine Research (Norway's largest center of marine science with almost 750 employees. Their main task is to provide advice to Norwegian authorities on aquaculture and the ecosystem of the Barents Sea, the Norwegian Sea, the North Sea and the Norwegian coastal zone.) https://www.hi.no/hi/en
- FHF – Norwegian Seafood Research Fund (FHF is a state-owned limited company owned by the Ministry of Trade, industry and fisheries, and financed by the industry through a levy on exports of Norwegian Seafood at 0,3 %. FHFs goal is to create added value to the seafood industry through industry-based research and development (R&D).)
- Norges Handelshøyskole (One of the leading business schools in Scandinavia.) https://www.nhh.no/
- Western Norway University of Applied Science (Ocean research group) https://www.hvl.no/en/research/ocean/
- NMBU (Mission is to contribute to the well-being of the planet. Their interdisciplinary research and study programmes generate innovations in food, health, environmental protection, climate and sustainable use of natural resources) https://www.nmbu.no/en
- Nofima (One of the largest institutes for applied research within the fields of fisheries, aquaculture and food research in Europe.) https://nofima.no/

- Norce (Working to find solutions that benefit the community and that increase sustainable value creation, both nationally and globally. NORCE carries out research in a wide range of technical and social science disciplines contributing to the development of knowledge for society and business.) https://www.norceresearch.no/
- SINTEF (Conducts research and innovation relating to the ocean space for national and international industry. Together with the industry and government, they are developing future-orientated solutions for sustainable utilization of the ocean.) https://www.sintef.no/ocean/
- The Norwegian Institute for Water Research (NIVA) (Norway's leading institute for basic and applied research on marine and freshwaters. The institute's research comprises a wide array of environmental, climatic and resource-related fields.) https://www.niva.no/
- The Norwegian Veterinary Institute (A biomedical research institute and the leading center of expertise in biosafety for fish and animals. Their main function is readiness and competence to avert health threats to fish, animals and humans. The core activities are research, innovation, monitoring, risk assessment, counseling and mediation as well as diagnostics.) https://www.vetinst.no/

Startups

- Blue lice (Blue Lice catch salmon lice in the larval stage before they attach themselves to the salmon. This reduces the number of infestations and thus reduces the need for treatment. By exploiting the salmon lice's natural instincts they eliminate salmon lice without any adverse effects on the fish or the ecosystem.) https://www.bluelice.no/
- Quantidoc (QuantiDoc AS is the pioneer in mucosal health management, helping customers take the guesswork out of fish health and welfare. The award-winning technology, Veribarr, verifies, objectively the health of barriers such as skin, gills and intestines. Quantidoc has also developed Veribarr Grid, the comprehensive database with over 10 thousand datapoints to help evaluate how fish experience their environment.) https://www.quantidoc.no/index.html
- SFD (SFD has developed a robust preventive solution against salmon lice. Verification and piloting have been carried out on large-scale commercial facilities in the period 2015 to 2019.)
- Submerged (Submerged delivers RollEye. Maintenance-free and autonomous technology for accurate machine vision measurements of sea lice counting and biomass measurement. RollEye is a multi-patented sensor solution allowing automatic and accurate measurements of lice and fish. Imagery from all parts of the fish and all positions in the pen are processed and analyzed in real-time. Anti-biofouling technology minimizes the need for maintenance.) https://www.submerged.no/
- SeaSmart (SeaSmart has developed a drone for continuous measurement of environmental conditions in the cage that is wireless, cost effective and maintenance-free. Information on fish appetite, stress level and welfare provide reduced feed, better planning and reduced mortality. SeaSmart will give continuous water quality information in the cages resulting in reduced mortality, increased production and good documentation.) https://seasmart.no/
- Konree Innovation Ltd (A developer of innovative robotic pest management and control solutions that transform the aquaculture industry and quality of life for

aquaculture fish species. Their solutions aim to solve the current obstacle to growth in open pen sea farmed salmon production due to sea lice issues and use sustainable technology to effectively manage fish health and fish welfare issues.) https://konreeinnovation.com/

- Viking Aqua (Building the world's most sustainable and technological land-based salmon farm. The facility is located in Skipavika, in the western region of Norway which is the world's leading competence center for aquaculture.) https://www.vikingaqua.no/
- Deepvision (Scantrol Deep Vision is dedicated to the development and sales of their fish measuring board, the FishMeter, and underwater camera system, Deep Vision. The company has worked in close cooperation with Institute of Marine Research in Bergen, and is a partner in CRISP, Center for Research-based Innovation in Sustainable fish capture and Processing technology.) https://deepvision.no/
- Anteo (A software company focusing on decision making systems for a sustainable aquaculture industry. Their real time solutions monitor and alert breach of biosecurity principles. This also leads to risk reducing measurements and possibilities for a closer cooperation in the industry and research community.) https://anteo.no/
- Aquabyte (Aquabyte surpasses modern farm monitoring products with their holistic software platform. The solution offers easy installation, continuous monitoring and multiple applications. Once the company has optimized its algorithms for salmon, it intends to move on to other kinds of fish as well as other markets.) https://www.aquabyte.no/
- Hauge Aqua (Hauge Aqua was established in 2012 and presents a new robust technology for industrial fish farming. The aim is to enable sustainable growth in the aquaculture industry that may feed millions, and offer a trustworthy and competitive alternative to today's aquaculture farms which are based upon open net pen production.) http://www.haugeaqua.com/
- Innomar AS (Develops high tech fishing traps which can be equipped with light as an attractor of fish, and sensors for catch monitoring and traceability. The fish traps catch fish in a sustainable manner that is gentle to the seabed. A team of world class researchers develop new tools based on scientific data observation, and their clients are fishermen, fish farmers and distributors.) https://www.innomar.no/
- Aquafarm (Aquafarm Equipment has solved some of the biggest challenges faced by modern aqua-culture industry. They have developed a cost-effective, closed fish cage for post-smolt production that prevents the escape of fish, drastically reduces the risk of salmon louse, and reduces the release of organic nutrients and waste into the surrounding environment.) https://aquafarm.no/
- Akvareforma (Strengthens the potential of Norwegian aquaculture with an eternal perspective by using principles from circular economy. By growing salmon in closed fish cages, using locally produced feed, and recycling waste, Akvareforma minimizes the land area used and associated climate footprint.) https://www.akvareforma.no/
- Fishency360 (A hardware and software solution for fish welfare that monitors fish health, lice, and growth in the pen. With a 360° view, the entire surface of every passing fish will be scanned and analyzed. Fishency uses technology to promote affordable sustainable development of the aquaculture industry.) https://www.fishency.no/
- Aquamedic AS (Delivers high-level scientific expertise to secure fish health and welfare. Zoo-sanitary analysis and advice on the control of infectious diseases and

parasites, support for the licensing of fish vaccines, therapeutics, and disinfectants in addition to welfare assessment of aquaculture equipment and methods are among their products and services.) https://www.aquamedic.no/

- Aquapro (Aquapro aims to build and develop a mobile processing facility that transforms sludge/waste from the aquaculture industry into combustible material. This fuel will have a great potential in cement production or district heating. The project is in the start-up phase and the focus is to develop the technology, as well as the creation of solutions for sludge handling, food and biowaste.) http://www.aquapro.as/
- Marimetrics AS (A technology company that designs and develops real-time diagnostic tools for the monitoring of fish health and welfare. Marimetrics is focused on helping operators in the aquaculture industry reduce mortality through the early detection of aquatic animal disease.) https://www.marimetrics.com/
- Aquatec (Ace Aquatec is a technology supplier with world leading experts in different scientific fields. Their focus is to provide the highest fish welfare – whether it's in the pen with their acoustic deterrents, or in the slaughterhouse with their electric in-water stunner.) https://aceaquatec.com/
- Aquacloud (AquaCloud was established in 2017 and is a big data project anchored in the aquaculture industry's need to solve common challenges in order to create sustainable growth. The project is part of NCE Seafood Innovation and began together with cluster members Lerøy Seafood Group ASA, Grieg Seafood ASA, Mowi ASA, Bremnes Seashore AS, Lingalaks AS, Eide Fjordbruk, and Bolaks AS. The project has developed substantially since 2017, and today the project involves an even broader group of leading aquaculture companies.) https://aquacloud.ai/

Other organizations

- NCE Seafood Innovation Cluster (NCE Seafood Innovation is a business cluster contributing to innovation and sustainable growth and development in the seafood industry.)
- Norse Lakseelver (Norske Lakseelver represents management teams in 108 salmon-carrying watercourses. The member teams are spread all over the country from Lakselv and Kongsfjordelva in the north, to Mandalselva and Audna in the south. Through the member teams, Norske Lakseelver represents about 10,000 fishing rights holders. It makes up about 70% of all licensees for salmon rivers in Norway.) https://lakseelver.no/en
- Leirvik (Leirvik AS is the leading EPC supplier of aluminum projects and related services for clients operating both on- and offshore. They guarantee quality products and services all the way from initial engineering for new projects to life-extending upgrades, maintenance and modification.) https://leirvik.com/about-us/
- Elanco (A global animal health company that develops products and knowledge services to prevent, protect and enhance animal health) https://www.elanco.no/index
- Coast Seafood (Coast Seafood started as an exporter of Atlantic salmon in 1994 and has since developed into a complete seafood company with stakes in different parts of the value chain. Today, Coast Seafood is engaged in aquaculture, processing, sales & marketing as well as air cargo handling.) https://coast.no/cms/
- Cargill (Cargill provides food, agriculture, financial and industrial products, and services to the world. Together with farmers, customers, governments, and

communities, they help people thrive by applying their insights and nearly 150 years of experience.) https://www.cargill.no/en/about-cargill-in-norway

- Benchmark Genetics Norway (Benchmark Genetics Norway is a breeding company that supplies eggs of Atlantic salmon.) https://salmobreed.no/benchmark/
- MSD Animal Health (MSD Animal Health is a global research-based company developing, producing and marketing veterinary pharmaceuticals and services.) https://www.merck-animal-health.com/species/aquaculture/
- Pharmaq (Pharmaq is the world's leading pharmaceutical company supplying the aquaculture industry. The company provides environmentally sound, safe and efficacious health products to the global aquaculture industry through targeted research and the commitment of dedicated people.) https://www.pharmaq.no/

Appendix II: Stakeholder perspectives

Participant	Job title	Type of organization
A	Director	Research institute
B	Member	Wildlife conservation group
C	Head Inspector	Governmental institute
D	PhD student	Research institute
E	Head of section	Research institute
F	Manager	Innovation Cluster
G	Business developer	Supplier

Appendix III: List of core options

1. Chemotherapeutants

Key Features: Chemical Therapeutants used to get rid of the sea lice

Description: Through most of its history, salmon aquaculture has relied primarily on chemical therapeutants (chemotherapeutants) to manage louse infestations. Several chemicals have been used, such as azamethiphos, pyrethroids, emamectin benzoate, hydrogen peroxide and benzoylphenyl ureas to reduce the amount of sea lice in salmon farms.

2. Mechanical delousing

Key Features: Mechanical measures used to force sea lice off the salmon

Description: In mechanical delousing, salmon are pumped through automated systems in which lice are physically removed using jets of pressurized water, turbulence and/or brushes. It involves flushing with water jets, flushing and brushing, or negative pressure and turbulence combined with flushing.

3. Cleaner fish

Key Features: Cleaner fish that naturally prey upon the sea lice used to remove sea lice from the salmon

Description: Various species of wrasse (family Labridae) and lumpfish (Cyclopterus lumpus) are used as facultative cleaner fish to remove parasitic sea lice from farmed salmon. Lumpfish are opportunistic generalist feeders and may graze on sea lice in salmon cages, especially when alternate food sources are limited.

4. Thermal delousing

Key Features: Hot water treatments to delouse the salmon farms

Description: Thermal delousing involves submerging fish in a chamber with water with a temperature of 28–34 ◦C for 20–30 s. The sudden increase in water temperature causes the lice to detach from the fish and lice are then removed by filtration of the treatment water.

5. Depth-based interventions

Key Features: Depth-based preventions segregate salmon from incoming copepodids at the surface, whilst leaving deeper sections of the cage open for water circulation

Description: Copepodids aggregate at shallow depths in the water column. This is likely an adaptation to improve host encounter rates since wild salmonids usually swim at shallow depths (especially during migration) and must regularly surface to refill their swim bladder. 'Depth-based' barriers can thus be used as a preventative strategy to segregate farmed salmon from incoming copepodids near the surface.

'Lice skirts' are walls of fine mesh or an impermeable material that encircle the upper several meters of a cage, preventing access to larvae. 'Snorkel' cages submerge salmon beneath the lice layer, providing a protected passage to the surface for the fish to refill their swim bladders. Skirts are widely used on farms and snorkel cages are emerging at a commercial scale. Other forms of depth-based preventions include enticing salmon to swim deeper using submerged lights and feeders.

6. Fresh-water delousing

Key Features: Exposing sea lice to fresh-water to remove them from the salmon

Description: Freshwater has potential to be used as an effective delousing method on farmed Atlantic Salmon. Bathing salmon in freshwater for a few hours is used for removing lice, which are sensitive to low salinities. Lice appear to be more susceptible to freshwater when used as a control strategy on farms, perhaps because the drop in salinity is more sudden and acute than occurs naturally.

7. Enhanced host resistance (through functional feeds)

Key Features: Enhancing host resistance through selective breeding

Description: One approach is to focus on salmon and improve their natural resistance to lice. A number of immune responses are triggered in salmonids following sea louse infestation, including inflammation, leucocyte proliferation and changes in mucous composition. One approach for enhancing host resistance is to provision salmon with 'functional feeds' that contain immunostimulatory additives.

8. Enhanced host resistance (through selective breeding)

Key Features: Enhancing host resistance through selective breeding

Description: Another approach that focuses on salmon and improves their natural resistance to lice is through selective breeding, in which long-term disease resistance can be obtained.

Appendix IV: Equations

Normalization and Aggregation Procedures in MCM

The Multicriteria Mapping methodology makes use of a normalizing formula to produce the policy option performance ranks. This employs a 'linear additive weighting' mathematical model based on the simple weight average of option performance:

$$r_i = \sum_c s_{ic} \cdot w_c$$

This equation means that the overall performance rank obtained for the i^{th}choice option (r_i) is the sum of the performance scores determined for that option under the c^{th}appraisal criterion (s_{ic}) each multiplied by the importance weighting on that criterion (w_c). The scores are normalized such that:

$$s_{ic} = (m_{ic} - m_{c,min}) \,/\, \sum (m_{c,max} - m_{c,min})$$

This equation means that the performance score for the i^{th} choice option under the c^{th}appraisal criterion (s_{ic}) is the ratio of the difference between the performance measure determined for that option (m_{ic}) and that for the lowest-performing option ($m_{c,min}$) with the difference between the performance measures determined for the highest – ($m_{c,max}$) and lowest – ($m_{c,min}$) performing options under that criterion.

Calculation of Outputs in MCM Analysis

Narrative Explanation of Successive Steps in Calculation

1 for each participant in the selected perspective;
for each criterion in the selected issue:
2 multiply pessimistic normalized scores by normalized weights;
this is 'pessimistic subrank'.
3 multiply optimistic normalized scores by normalized weights;
this is 'optimistic subrank'.
4 subtract pessimistic subrank from optimistic subrank;
this is 'delta'.
5 sum half delta with pessimistic subrank;
this is 'median'.
6 divide delta by median;
this is 'ratio uncertainty'.

Mean Ratio Uncertainty

7 across each criterion in the selected issue;
across all participants in the selected perspective:
8 take mean of ratio uncertainties;
this is 'mean ratio uncertainty'.

Mean Ambiguity

9 across each criterion in the selected issue;
across all participants in the selected perspective:

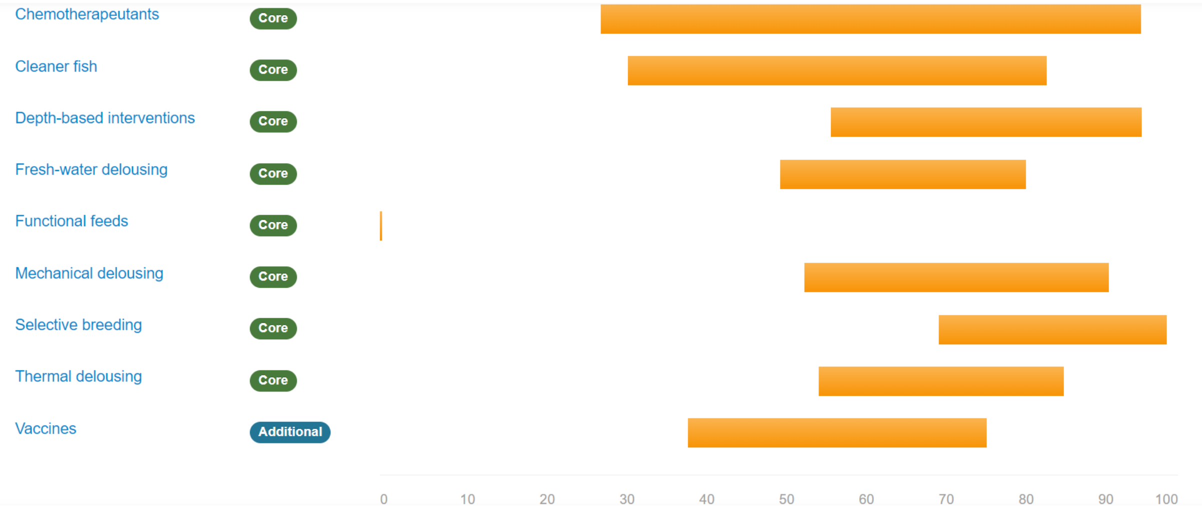
10 take mean of pessimistic subranks;
this is 'mean pessimistic subrank'.

11 take mean of optimistic subranks;
this is 'mean optimistic subrank'.

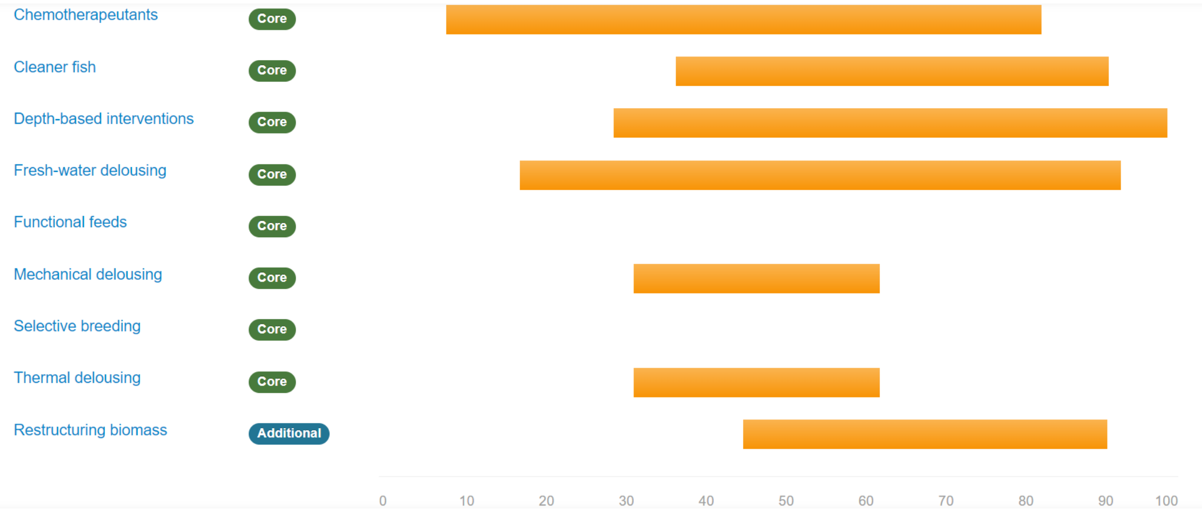
12 subtract mean pessimistic subrank from mean optimistic subrank;
this is 'mean ambiguity'.

Appendix V: Individual rankings

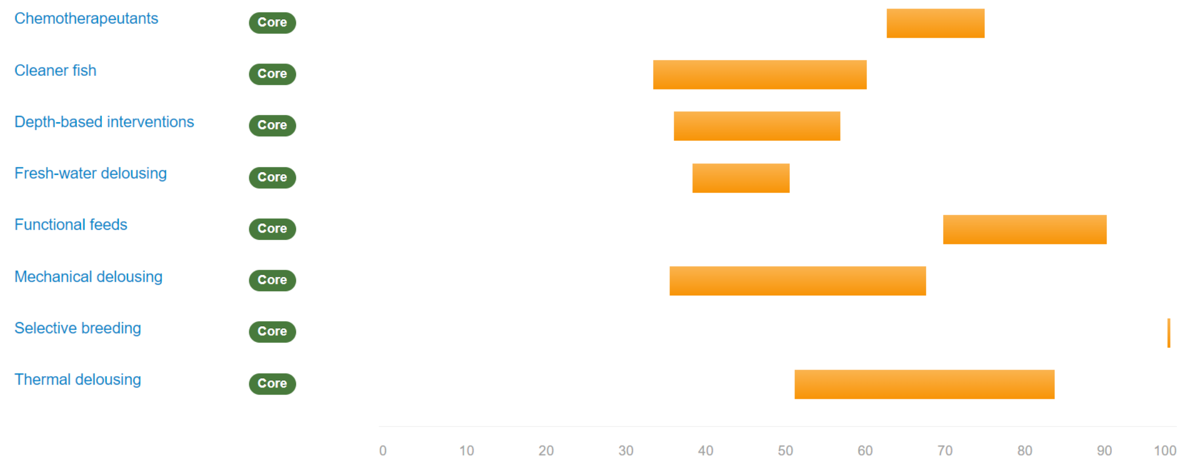
Participant A



Participant B



Participant C



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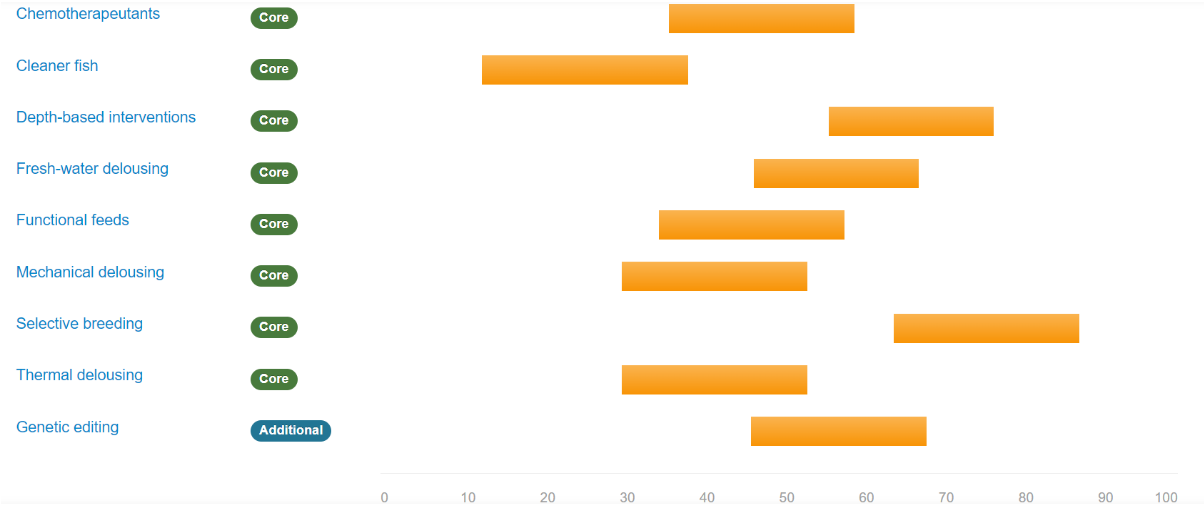

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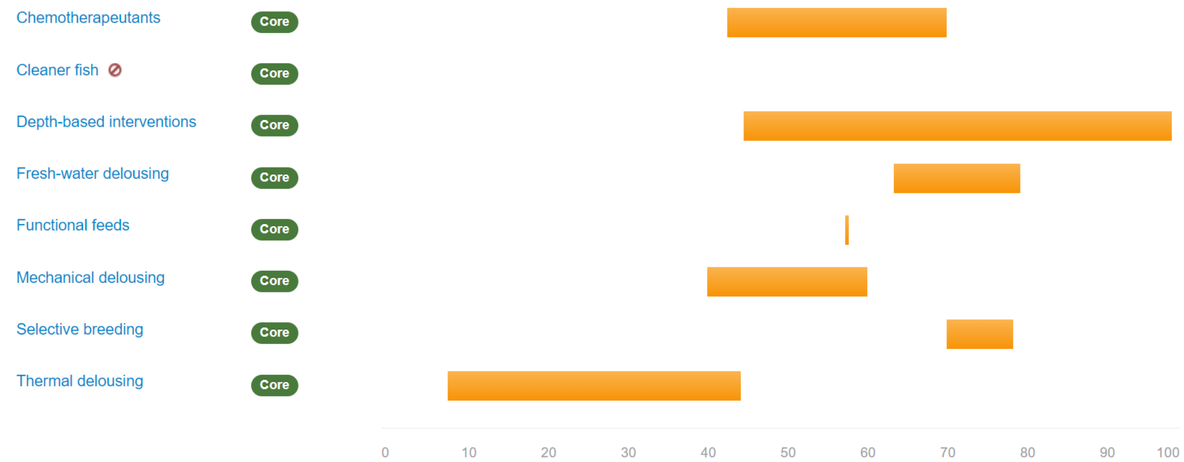

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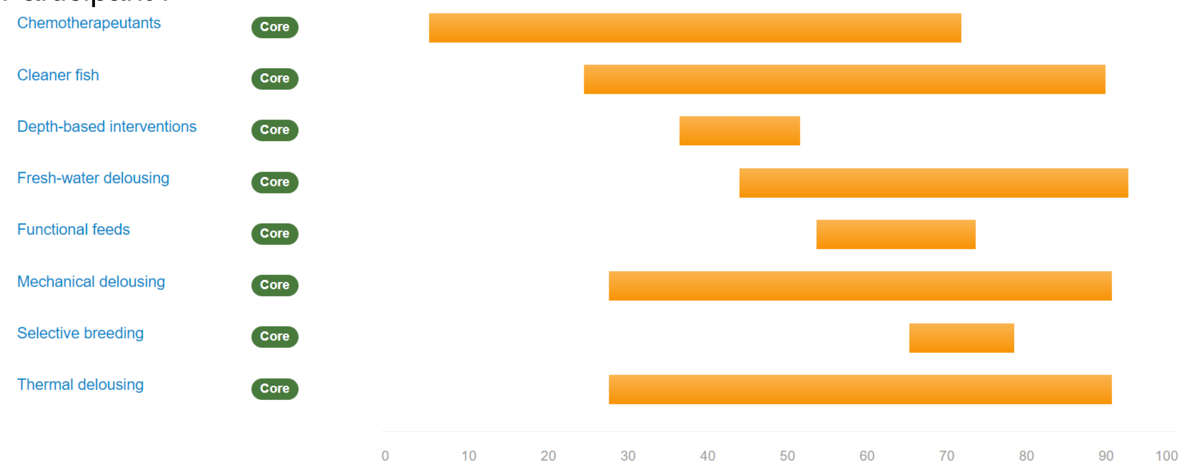
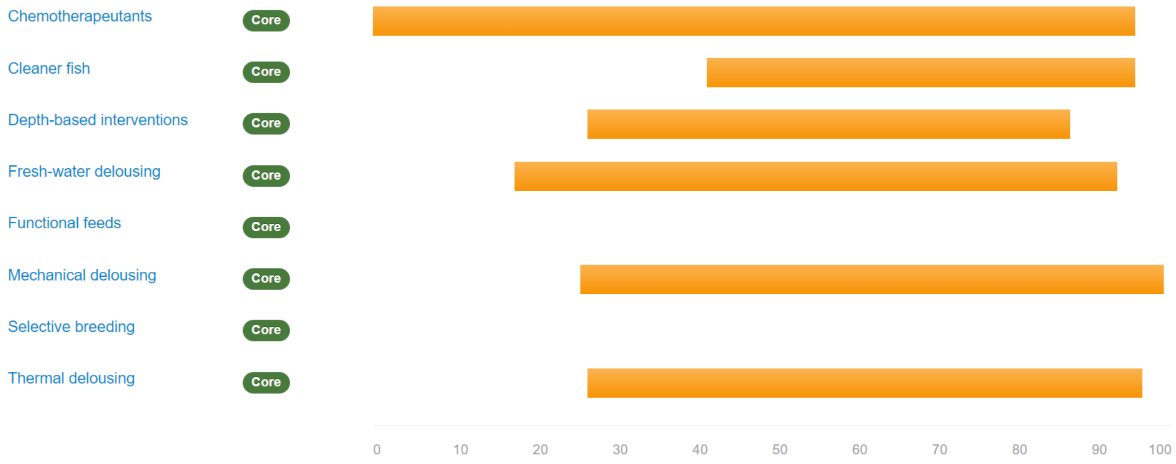


Participant G



Appendix VI: Keywords for criteria

Effectiveness: control, removal, effectiveness, benefits

Welfare: effect/impact on fish health/welfare

Cost: economy, economics, cost

Environmental impact: effect/impact on environment

Availability: available, availability, access

Dependency on environment: dependent/dependency on environment

Resistance: resistance, resistant