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RISK MANAGEMENT IN AQUACULTURE – INTEGRATING SUSTAINABILITY PERSPECTIVES

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ABSTRACT

The aquaculture industry in Norway produced 1.3 million metric tons of fish in 2014, and further expansion is expected if the main sustainability challenges related to production and operation are mitigated. Major biological, operational and environmental challenges are parasite infection, fish escape, fish health, human injuries and fatalities. The larger farms, exposed locations, and sustainability challenges related to more production of salmon, increases the need for efficient decision support methods and risk management. The combined effect of the technological development, with increased remote operation, autonomy and automation, and the production and operational challenges related to sustainability means that an interdisciplinary and systemic approach integrating risks to the environment, as well as to fish welfare and human safety, is needed. Therefore, the development of such an approach is outlined in this paper. Potential users are fish farming companies, but the paper also addresses the need for an industry standard for sustainability and risk performance monitoring, which should be of interest to authorities and the whole industry. The paper concludes that risk management and sustainable development are complementary concepts that benefit each other because efficient risk management is decisive for achieving sustainability in aquaculture.

INTRODUCTION

The aquaculture industry in Norway has grown from small scale production in the 70's into large enterprises reaching 1.3 million metric tons produced fish in 2014 [1]. Further expansion is expected and could reach 5 million tons of fish per year by 2050, if the sustainability challenges related to production and operation are mitigated [2].

Fish farms contain an increasing amount of fish at the same location [3]. Major biological, operational and environmental challenges are parasite infection, fish escape, fish health, human injuries and fatalities. Sea lice is identified as the greatest environmental challenge in Norwegian fish farming [4]. Lice or parasite infection may cause injuries to the farmed fish, it increases the use of medicaments, and the risk of infections to

Figure 1. Fish farm, photo taken by NTNU.

wild salmon. Delousing operations are complex and involve several actors and the use of cranes and heavy equipment, and may therefore be hazardous to the both the fish and the human operators [5]. In 2014, the economic losses in the Norwegian aquaculture industry related to lice were estimated to be 3-4 billion NOK; approximately 400 million Euro [6]. This amount was the same for 2016, which indicates that lice infection is a persisting challenge [7].

The use of filter skirt around the structure, extensive cleaning of the net cage, and lice-eating fish (wrasse) are the most common countermeasures to reduce lice infections. The use of chemicals is still prevalent, although new methods, like laser and the use of fresh or tepid water have been developed. The use of a ‘snorkel’ sea lice barrier technology, which restricts salmon from accessing the surface, except via a vertical chamber impermeable to sea lice larvae, has also been suggested [8]. Although these measures are considered more environmental friendly, systems for efficient prevention would spare the fish for treatments, and improve the predictability and cost-efficiency of fish production.

Fish escapes from fish farms may present a threat to the biodiversity of the surrounding environment, as escaped fish might genetically interfere with other salmon species or compete with other species for resources [9]. Successful measures have been implemented to reduce the number of fish escapes due to technical deficiencies and breakdown of entire fish farms, e.g., the introduction of the Norwegian technical standard NS 9415 [3]. Still, in between 100 000 – 400,000 salmon and trout have escaped yearly since 2007 [10].

Previous studies indicate that fish health and welfare are sometimes prioritized higher than human operator safety [11]. Decisions concerning safety during operations are often left to the operators [12]. In the Norwegian aquaculture industry, there were 33 fatalities from 1982-2013, but the fatality rate has decreased in recent years [13-14]. Typical hazards related to fish farming has been identified to include drowning, electrocution, crushing-related injuries, fatal head injuries, and hydrogen sulphide poisoning. Injuries are often caused by slips and trips, resulting in falls, and loss of control. Typical risk factors are crane operations, heavy lifting, wet and slippery surfaces and storm-related rushing water, diving conditions, work alone, night-time conditions, and rough weather situations [15].

The farmed salmon production volumes are growing, larger structures are installed, and more exposed sites are taken into use, and these trends continue. Farmers already using more exposed locations report challenges related to reliable production [16]. In addition to a rough, wet and demanding work environment, the operators are exposed to efficiency pressures, because of the nature of the biological production. The performance of new technologies and risks related to its utilization, for example, in terms of remote operation and autonomy due to the trend of moving fish farms to exposed sites offshore [17], significantly impact future requirements to aquaculture production. In line with current trends in the general food production industry, aquaculture is becoming more automated, and further developments are expected to become available in near future [18].

The larger farms, more exposed locations, and major sustainability challenges related to more production of salmon, increases the need for efficient decision support methods and risk management. Today, the aquaculture industry must comply with requirements in laws and regulations enforced by five different authorities, i.e., Directorate of Fisheries, the Norwegian Food Safety Authority, the Norwegian Labor Inspection Authority, The Norwegian Maritime Authority, and the County Governor. Hence, risk management in a holistic manner is a challenging task.

In the Norwegian White Paper “Strategy for an environmentally sustainable Norwegian aquaculture industry”, five primary environmentally oriented areas (and goals) for the future development of the industry were established: (i) Disease (including lice); (ii) Genetic interaction (escapes); (iii) Pollution and discharges; (iv) Zoning; and (v) Feed and feed resources [19]. [20] has outlined overall sustainability indicators for the Norwegian aquaculture industry. They claim that the focus of the authorities is on the environmental aspect and that more emphasis should be put on economic and social aspects of sustainability. [21] also state that the public opinion is mostly concerned with the environmental risks.

Autonomous systems for aquaculture operations and remote monitoring of sites may contribute to less exposure of the human operators to the harsh operating environment, and give better means for relevant data collection and measurements. Introduction of novel technology, however, also imposes possible new risks to humans, fish and the environment. The combined effect of the technological development with increased remote operation, autonomy and automation, and the production and operational challenges related to sustainability means that an interdisciplinary and systemic approach to risk management is needed, integrating risks to the environment, as well as to fish welfare and human safety. Development of such an approach is outlined in this paper. Potential users are fish farming companies, but the paper also addresses the need for an across industry standard for sustainability and risk performance monitoring, which should be of interest to authorities and the whole industry.

The paper is structured as follows: Section 2 defines the concepts of risk, risk management, sustainable development and compares their main characteristics. Section 3 presents the integrated risk management framework and discusses its main constituent parts. The last Section states the conclusions and further work.

RISK AND SUSTAINABILITY – DIFFERENCES AND COMMONALITIES WITH FOCUS ON AQUACULTURE

Risk is most often defined by the answers to three questions: (i) what can go wrong?; (ii) how likely is it?; and (iii) what are the consequences? [22]. Thus, risk related to an activity can be represented by [23]:

$$\{e_i, p_i, c_i,\} \tag{1}$$

Here, $\mathrm{e_i}$ represents the hazardous event i, $\mathrm{p_i}$ is the probability, and $\mathrm{c_i}$ the consequence. Some people would say that the $\mathrm{p_i}$ represents uncertainty about the event, but following the arguments of [24], the probabilities for two different events could be the same, but the strength of knowledge used to establish the probabilities could be very different. Risk can then be defined by:

$$\{a_i, c_i, q\}|k \qquad (2)$$

Here a is a hazardous event, c is consequence of a, q is a measure of uncertainty, and k is the background knowledge used to determine a, c and q [25]. In this definition, uncertainty is the main constituent part of risk rather than only probability.

The concepts of sustainability and risk may be considered complementary when studying and managing environmental consequences of human behavior [26]. Both concepts are much debated, but the most well-known definition of sustainable development is stated by [27]: "Development that meets the need of the present without compromising the ability of future generations to meet their own needs". In general, sustainability has both environmental, economic and social dimensions.

Risk management is decisive in decision-making processes, and important to achieve safe and cost-efficient design and operations of complex systems [28]. Risk management consists of risk assessment, risk monitoring, control, and follow-up of risk [22, 29]. The concept of risk is therefore the foundation for risk management.

According to [30], risk management for salmon aquaculture is complex and challenging as there are several social and ecological uncertainties, and conflicting values. They propose a three-step approach to understanding and developing better structured risk management decision frameworks. The first step focuses on regulatory decisions and structure, the second step clarifies different stakeholders' objectives and means to achieve them, and the third step is to consider performance measures that explain what is relevant for decision makers to understand. [31] found that fish farmers mostly consider future salmon price, diseases and different regulatory issues as the most important risk sources.

In risk assessments of socio-technical systems, the predominant focus is on risk for human injuries and fatalities, and long term environmental effects are often overlooked. In general, typical risk analysis methods in the design phase are preliminary hazard analysis (PHA), fault tree analysis (FTA), failure mode, effect, and criticality analysis (FMECA), and event tree analysis (ETA). During operation, safe job analysis (SJA) may be performed [22]. Ecological risk assessment involves the analysis and evaluation of the risks posed by the presence of substances released to the environment on, in theory, all living organisms [32].

Fig. 1 illustrates some of the different aspects of relevance for risk management identified in literature today, categorized within the tree pillars of sustainability, based on [6, 9, 13-14, 21, 33]. In Norway, the primary environmental risks related to aquaculture are related to fish escape and lice infestation, impacting genetic interaction and the spreading of disease. These risks are also related to the economic and social dimensions of sustainability, due to the potential losses of livestock and the hazardous work operations in which the human operators are involved.

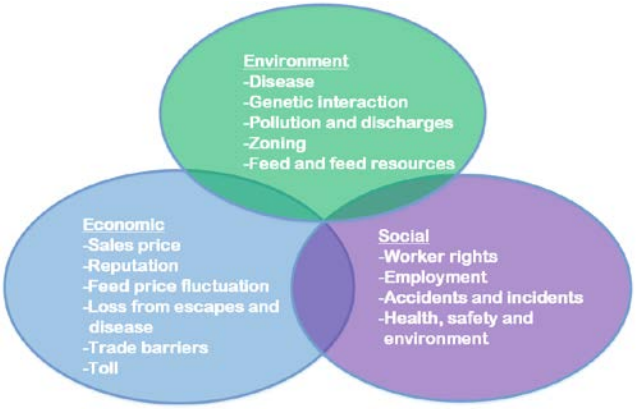


Fig. 1. Aspects relevant for risk management in the aquaculture industry, categorized within the three pillars of sustainability. Based on [6, 9, 13-14, 21, 33].

Table 1 presents the main characteristics of risk management and sustainable development, related to the aquaculture industry. Risk management and sustainable development focus on the future performance of systems, but the purpose of risk management is different from sustainable development. Whereas risk management mainly focuses on preventing hazardous events, i.e., incidents and accidents; sustainable development is more focused on improving "continuous" processes and conditions. Improving energy efficiency in aquaculture would typically be a management goal, which could be related to improved sustainability (and cost efficiency), however, the assessment of any negative consequences to human operators related to implementation of new technology and new operational practices to increase energy efficiency would be the responsibility of the risk management professionals. Reducing the use of harmful chemicals, on the other hand, would be related to both improved sustainability and risk management, as the presence of less hazardous substances could reduce the occurrence of harmful spills affecting both the risk for human operators and the environment. These examples show that risk management, sustainability and sustainable development have both differences and commonalities.

The time horizon of risk management is usually shorter and include, e.g., follow up of daily operations and include, for example, SJA, but also more long term planning and risk assessments related to future designs and operational practices and procedures. The goal of both areas is to be proactive, i.e., avoid a negative development and prevent hazardous events. Proactive risk management means that the focus is more on preventing incidents and on the analysis of causes to hazardous events, rather than "firefighting", i.e., focusing on barriers, which reduce consequences if hazardous events should occur.

Table 1. Comparison of the concepts of risk management and sustainable development considering aquaculture. Adapted and further developed from [26].

Characteristic	Risk management	Sustainable development
Purpose	Ensure safety by preventing incidents and accidents	Ensure development which does not compromise future harvesting from the ocean
Approach	Ideally proactive	Proactive
Perspective	Fragmented, several different authorities to report to	Life cycle perspective, but often not integrated in daily operations
Time horizon	Short to medium	Medium to long term
Uncertainty	Part of suggested definition of risk, but most often only considered implicitly (cf. definition (1) with (2))	Implicitly.
Decision making principle	Cost-benefit	Precautionary principle. Consequences and effects are mostly relevant.
Consequence dimensions	Human injuries/fatalities, environmental impact, financial losses	Economic, social and environmental
Level of detail	Humans, groups, technical components and systems	Systems
Performance measurements	Monitoring and follow up important, e.g., in terms of trending and safety indicators	Monitoring and follow up important, e.g., in terms of trending and sustainability indicators

Both areas involve considerations of uncertainty, even though this aspect is traditionally not explicitly communicated in risk management [34]. The response to uncertainty involved in sustainable development is decision-making by use of the precautionary approach, which may be difficult to follow for industrial production, because it may imply a very risk adverse approach, and implementation of new technology may become difficult. The future goal of increased salmon production in Norwegian aquaculture may be challenging to achieve when using the precautionary principle. It is, nevertheless, possible to use the precautionary principle as a basis for determining acceptable risk, as part of risk management. More commonly used in risk management is the as low as reasonable practicable (ALARP) principle, which implies cost-benefit considerations. (See, for example, [22, 34] for more information on acceptable risk). Risk of an activity is often expressed quantitatively or in terms semi-quantitative categories in risk matrices, whereas sustainability may be communicated through visions and strategies [26]. More quantitative means for expressing the level of sustainability has been developed, e.g., for the Norwegian fishing fleet [36].

Risk management is focused on the specific company's needs and the business objectives, and to fulfill requirements in regulations. Hence, the focus is mostly on human operators, organizational issues, and technical systems and components. Sustainable development implies a more overall societal and global focus, for example, on loss of biodiversity and eutrophication. Sustainable development might be hindered by the concept of the "tragedy of the commons" [37]. In many cases, however, improved sustainability can also benefit business [38]. In addition, different aspects within sustainability are related to different requirements from authorities to gain permission for activities. A major challenge for efficient risk management in aquaculture is the need for complying with regulations from the five different authorities, as previously mentioned.

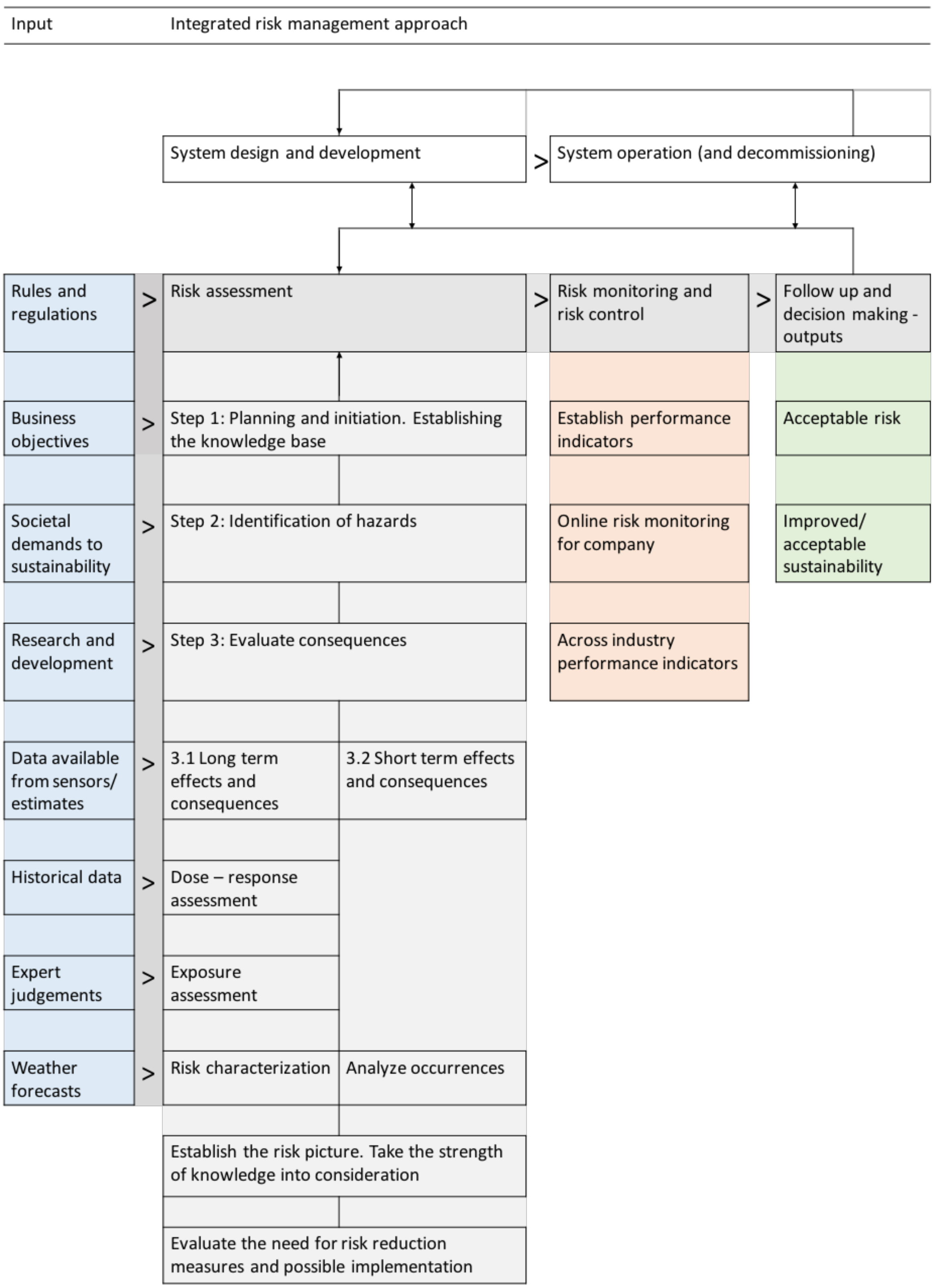
An important part of both risk management and sustainable development is "continuous improvement". Monitoring and follow up is part of the risk management definition. Sustainable development is focused on enabling change that reduces human impact on the environment. For both concepts, performance measurement and monitoring in terms of use of indicators and trending is important to be able to evaluate the risk level or to determine if a system or activity is becoming more sustainable.

AN INTEGRATED RISK MANAGEMENT FRAMEWORK FOR AQUACULTURE

The challenges related to increased aquaculture production and the current problems related to both environmental impact and personal injuries and fatalities, along with the fragmented regulations, means that there is a need for an integrated risk management approach. This approach should be proactive, but should also take aspects from sustainable development into account. Table 2 shows the overall concept, which has a life cycle perspective, including risk management during system design and development, operation, and decommissioning. Different risk analysis methods may be applicable for the life cycle phases, as discussed in the previous Section.

The risk management approach considers the risk perspective and definition (2), and the characteristics from Table 1. It emphasizes consequence evaluation of both short term and long-term effects, and it has a company focus, as well as an across industry focus. The steps from [30] are also reflected in Table 2 with respect to input to risk management, planning and initiating, and risk monitoring and control. The approach in Table 2 is further explained in the following Subsections.

Table 2. Integrated risk management approach for aquaculture.



Input

Input to risk management may come from detailed sensor data to overall societal expectations, as well as from rules and regulations by different authorities. It is insufficient to have separate reporting systems and databases for complying with the requirements from the different authorities. An integrated risk management system means that information from all reporting systems, for example, escape of fish, presence of lice, illnesses, technical failures, maintenance reports, etc., should be retrievable and possible to utilize in the risk management system. Further, sensor data and estimates become increasingly important for more exposed facilities with larger amounts of fish and remote surveillance of the condition of the farm.

Increased remoteness and harsh environmental conditions will demand higher abilities for observation and condition monitoring of the fish farm sites. The trend is towards operation centers monitoring several production sites. Lack of redundancy in sensors and communication links from shore to the offshore site may be a challenge. Accurate information from the monitoring system is important for remote operation and control, for example to determine the amount of feed necessary for the fish. Sensor data used in the aquaculture industry have traditionally been limited mainly to visual observation in terms of cameras and measurements of, for example, the temperature and oxygen content in the water. Other types of sensors are gradually being implemented, such as hydro acoustics, which improves the possibility for attaining information remotely related to the environment, the fish welfare, and the structural integrity of the fish cages (for example, water current profiles and anchor loads).

Sea-based aquaculture is exposed to strong environmental forces from winds, currents, waves, and weather conditions. Fish farms today have well developed operational procedures for daily operations and maintenance. However, efficiency in operation is dependent on the human operator and his/hers experience, which means that the decision basis is highly qualitative. Not all operational data is possible to measure quantitatively, for example, related to human and organizational factors, and hence expert judgments and subjective probabilities have to be used in the risk assessments.

Risk assessment

The Norwegian fish farming industry is decreed to implement internal control to comply with regulations statutory in the Aquaculture Act and Working Environment Act, respectively [39]. A living internal control system consists of four steps: (i) initiate process, (ii) map and assess risks, (iii) plan and prioritise measures, and (iv) follow-up activities. These steps should be repeated in a continuous loop, as indicated in the risk management approach in Table 2. Identifying hazards, risk assessments and mitigation are important tasks in this work. Risk assessments shall be conducted and documented, and risk-reducing measures are to be prioritised and implemented. As of today, the fish farming industry shall systematically manage risks to fish welfare, food safety, maintain the technical standard of fish farm structures and vessels, personnel safety, health and work environment, as well as to mitigate threats to the surrounding environment [39].

The risk assessment procedure in Table 2 combines the steps related to risk assessment of socio-technical systems, and ecological risk assessment. Ecological risk assessment focuses more on long term effects and dose-response relationships, which implies utilization of deterministic and physical models. The exposure assessment includes what exposures can be expected under different conditions/scenarios. The risk characterization step is hence an assessment of how likely it is to experience an adverse effect in a population [36, 40].

For an aquaculture company, the risk management approach should be developed on a more generic basis at the company level, and then more tailor made versions could be developed for different regions and facilities. Risk assessments for each facility must be performed and is a requirement in the current regulations [39]. Hence, the companies can use existing analyses as a starting point. The challenge is to utilize the results from risk assessments in daily operations and for both short term and long term operational planning.

Risk assessments are successful if stakeholders, such as fish farm operators and managers, achieve a greater understanding of the risk picture in their operating environment. The operators are important to include in the risk assessments because they possess hands-on experience, are involved in daily operations and decisions to prevent injuries and accidents. Following the internal control regulations and the approach in Table 2, managers should follow up by documenting the risk assessment process and establish a shared plan for implementation of risk-reducing measures. Prioritization of the measures is closely related to budget discussions at the management level, which implies that management is familiar with the operational risk levels [39].

Authorities use risk assessments performed by aquaculture companies as a “quality measure” of risk management, during audits or accidents investigations. They also identify which risk-reducing measures the company has identified and possibly implemented. Thus, it is important for the aquaculture companies to document that they have performed thorough risk assessments as the basis for mitigating risks inherent in the operating environment [39].

Risk monitoring and risk control

A structured and sufficient decision support system for risk monitoring and risk control during operation should be part of the integrated risk management system. Risk monitoring and control can be performed at different levels, both at an industry level and at a company level. There is a need for both types of performance measurements. Performance indicators are needed, not only for safety, but for sustainability. Often, health, safety and environment (HSE) is vaguely defined as part of the social dimension of sustainability, and “counting” injuries is the main focus, see, e.g., [20]. This is insufficient both at an overall industry level, and at company level.

Industry: The successful risk level project (RNNP) for the Norwegian oil and gas industry [41-42] could serve as a background for developing an across industry performance monitoring system for sustainability in aquaculture. [43] emphasizes the potential for interdisciplinary cooperation and transfer of knowledge between different industries.

The RNNP project was introduced in 1999-2000. The main objective is to map and improve HSE conditions in the petroleum industry. It is a management tool and process which consists of both quantitative and qualitative methods. RNNP is an important process for supervision of the risk level in the oil and gas sector, and contributes to a shared understanding of the risk by companies, unions and government agencies. The overall indicator in RNNP is major hazard accidents, normalized by number of work hours [44]. Correspondingly, a clearly defined sustainability indicator could be developed and used by authorities and the aquaculture industry to communicate the condition and status of the aquaculture sector to the public.

Companies: Decision support systems for fish farm operators are currently limited and operational decisions are experience-based. In general, the operators monitor the fish by using a camera surveillance system at specific locations, and based on their own experience, they assess the current health of the fish. Also, in the few existing operational centers monitoring several locations, decisions are mainly experienced-based. The Norwegian Food Safety Authority and others perform regular manual inspections. In other industries, such as the automotive and oil and gas, advanced computerized diagnostics and prognostic systems are prevalent.

The general advancements in enabling technologies, which are important for implementing more autonomy in systems and operations, support the development of novel online decision support systems, including online measurements, communication technologies, information gathering and processing technologies (data models and hardware), visualization techniques and interaction modes between users and support systems (software platforms). Future online decision support for safer operation should involve risk assessment and modeling, data models and representation, sensors and communication technology, autonomous operations and measurements, visual computing, human-machine interface (HMI), and organization theory, as well as system integration [45].

There is a potential for improved decision support systems for fish farm operators providing information about the condition of the fish farm, i.e., combining, for example, online condition and environmental data, as well as historical data from performance measurements. This includes predictions of potential hazards, such as parasite infections, combined with weather forecasts and measurements of currents, waves and winds, and parameters for fish welfare, such as oxygen levels and appetite. Sustainability indicators, such as fish welfare, that present critical operational information to the operators and managers need to be developed. Improved decision support could give the operators more time for planning of possible risk mitigating measures in operation, as early warnings could be given and procedures initiated.

Future decision support systems for fish farms should include risk to humans and the environment, as well as fish welfare or health management. Implicitly, part of the economic dimension of sustainability is then also covered, for example, with respect to production losses and company reputation. Cheaper sensors and increased data processing capacity should lead to improved monitoring of the health condition of the fish farm. Condition and operational data can be applied in online prognostic and risk models. Figure 2 illustrates a future decision support system at a conceptual level.

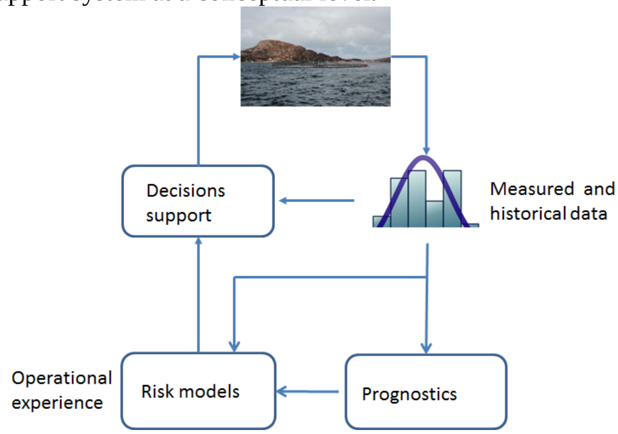


Figure 2. The online risk monitoring and integrated health management system.

Risk models that can provide online decision support for safer operation in aquaculture have not yet been developed. Such approaches are under development and much work remains to be conducted in the realization of their potential both with respect to implementation in the industry and their theoretical basis, especially when it comes to risk representation, quantification, uncertainty, and time resolution on hours and minutes.

Risk assessment methods are currently based on statistical data and probability models. The utilization of data based models could reduce the level of uncertainty and provide means for prediction of information, handling of large data loads, as well as fusing of data from different sources. The value of sensors oriented towards evaluating asset risk is widely appreciated across industries from nuclear, aerospace to oil and gas industries [46], amongst others. Despite this, their application in online decision support systems capable of monitoring assets covering large areas has been hindered by, e.g., the cost of wired sensor networks, complex installation and space limitations. Thus, many sensor technologies are confined to inspection applications. An online risk monitoring system with integrated prognostics and health management for fish farms might reduce the number of serious undesired incidents, such as parasite infections, fish escape and personal injuries. The system needs to rely on online sensor data for data acquisition and should suggest an optimal sensor configuration for a remote sensing system. Ideally, such a system should detect and track the condition and operational health of the fish farm and calculate the occurrence likelihood of different operational risk scenarios, providing sufficient lead time to enable implementation of risk mitigating measures when necessary.

Evaluation and follow up

The results from the risk assessments, risk monitoring and control needs to be evaluated and followed up on a regular basis. This implies that acceptable levels of risk and sustainability have to be determined. Results from RNNP [41] is presented annually to the public. In a company, trending may be performed weekly or monthly. Information presented in an online risk monitoring tool may update trends continuously.

DISCUSSION AND CONCLUSIONS

This paper presents an integrated risk management approach which is based on a risk definition emphasizing uncertainties. This is beneficial for including a risk assessment procedure focusing on both long term and short term effects, and sustainability aspects. The framework also includes risk monitoring and risk control during operation and briefly outlines the need for sustainability indicators, both at an industry level, but also at a company level. For companies, an online risk monitoring and health management system could be beneficial for decision support for human operators, especially when fish production is moved further offshore and becomes more remotely operated.

An expected growth within the aquaculture industry combined with larger and more remote sites, is fueling technological development and implementation of automation, autonomy and remote operation. To assure and control future potential risk to humans, fish welfare, and the surrounding ecosystems, it becomes crucial to have a risk management approach that can account for the possible risks related to expansion and automation of operations further offshore. Autonomous solutions may contribute to risk reduction by decreasing the exposure of human operators to harsh working conditions. It is important, however, that an integrated risk management approach focuses on sustainability to make sure that the new technical solutions are not moving the risk from one sustainability dimension to another, for example, from direct impact on human health to indirect impact on human health, through posing risk to ecosystems.

To achieve efficient decision support during operation of fish farms, risk monitoring and risk control are important activities. This implies increased use of data and combining measurements from sensors with historical data and expert judgments. Currently, lack of efficient data gathering systems, databases, insufficient data handling procedures and systems may challenge the development of such decision support systems, both at a company level, but also for gathering data across the aquaculture industry, similarly to, e.g., the RNNP project in the Norwegian oil and gas industry. Hence, it is important to focus further research work on methods and standards for data collection and models, development of online risk models, and safety and sustainability performance indicators.

Sustainable development aims to promote a system which is robust and able to survive existential hazards. Risk management is a tool, which can be used to measure and reduce specific hazards [26]. Hence, risk management and sustainable development are complementary concepts that benefit each other. Global risks at a societal level are introduced when sustainable development goals are not achieved. Nevertheless, sustainability is related to industry and company practices and needs to be operationalized at lower levels. Hence, efficient risk management is decisive for achieving sustainability in aquaculture.

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