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Strategies and methods for reducing risk

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Thesis for the degree of Philosophiae Doctor
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PREFACE

This thesis is prepared in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the Department of Marine Technology, under the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU). My supervisors have been Professor Ingrid Bouwer Utne and Professor Stein Haugen at the Department of Marine Technology.

The PhD work was mainly funded by the Research Council of Norway through SFI Exposed, project no. 237790/O30. The data collection and writing of one article was funded by the Norwegian Seafood Fund, project no. 900835.

The thesis consists of two parts. The first part provides a synthesis of the objectives, background material, relevant literature, and contributions of the PhD project. The second part is a collection of five research articles which describe the research studies and main results obtained.

ACKNOWLEDGEMENTS

The motivation for a PhD came after several years working with safety management and accident prevention in the marine industries as a researcher in the research institute SINTEF. SFI Exposed made this possible. Along the way I have met managers, staff, operators, and technology manufacturers in the fish farming industry who have shared their knowledge and communicated challenges and needs in the most generous and honest manner. By answering my endless questions, you have contributed significantly to this thesis.

I am indebted to my supervisors at the Department of Marine Technology, NTNU. Professor Ingrid Bouwer Utne and I started our collaboration during previous R&D projects, and eventually she convinced me that a PhD was within reach for me. Professor Utne has reminded me to maintain focus on the PhD in times of too much SINTEF contract work and lifted the academic quality of my work. My second supervisor, Professor Stein Haugen, has contributed to my work with practical insights from his own industrial work and possesses a remarkable ability to communicate risk theories in a comprehensible way. I am also indebted to Dr. Xue Yang, former post doc at NTNU IMT, for teaching me patience in tedious data analyses. Thank you for all the hours spent together interpreting several hundred fish escape registrations and for becoming a good friend.

I am part of excellent research teams in SINTEF. The first fish escape project was conducted together with Dr. Trine Thorvaldsen and Helene Katrine Moe. My dear colleague Trine has cheered me up during times of frustration. We have worked together for a decade and share a passion for safety for fishers and fish farmers. I am also grateful for the support from SFI Exposed centre director Hans V. Bjelland, research director Gunvor Øie and colleagues in SINTEF Ocean.

During the years as a PhD student at NTNU IMT, I have met many clever PhD and post doc candidates. Our lunches are memorable. Many of you have become SINTEF colleagues. I have received professional and kind support from the staff at the department. I have had two roommates during the years at IMT, Siri and Reza. Your drive to finish your own work inspired me. Thank you for the "brain breaks" and interesting discussions!

My family also has a share in this thesis—by silently accepting me arriving late for dinners and being absent-minded in busy periods of PhD or SINTEF work. Thanks to my spouse Kristin for dinners and her loving support. Thanks to my children Ingrid and Tormod—you have grown up to be wise young adults. Our entertaining and mushroomhunting Lagotto dogs Fia and Maja make us go outdoors in all kinds of weather. Thanks to all my friends as well for cheering along the way.

I grew up far from the oceans, in Alvdal municipality in the mountain areas of Eastern Norway. My parents kept focus on the important things in life: family, education, farming, animal welfare, and safety and wellbeing for us all. Thank you, Mom and Dad, for giving me a solid foundation for life. One important thing my three elder brothers and I learnt was to always finish work that you have started.

The PhD project is now finished.

SUMMARY

Norway is the largest producer and exporter of farmed Atlantic salmon and rainbow trout worldwide. The national ripple effects of the fishing industry are significant. New concepts are being developed and tested for fish farming in exposed locations offshore, but still the dominant fish farm technology remains floating net cages in coastal areas. Hence, Norwegian fish farming faces sustainability and reputational challenges due to farmed salmon escape and salmon lice. Fish farm operations are characterised by five risk dimensions: risk to material assets, personnel, fish welfare and health, environment, and food safety.

The main objective of this PhD project is to develop knowledge and methods for improved management of safety in exposed sea-based fish farming. Fish escape has been used as the study case. The following summarises the contributions:

- A new categorisation system for fish escape event data has been developed. The registered fish escape events are reanalysed and re-categorised into i) hazardous event, ii) direct causes, iii) underlying factors, and iv) coupling factors. Four main groups of hazardous events are established: Fish escape due to 1) a submerged net, 2) holes in the net, 3) loss of fish, 4) and structural damage without damage to the net. The fish escape data is reanalysed using the new categorisation system according to the consequence of the event (size of escape). The most frequent hazardous event is "holes in the net," which are most often caused by net chafing by equipment/structures or operational failures. Fish escape scenarios are drawn based on the reanalysis of the Fdir database, with the hazardous event as the top event, direct causes at the second level, and contributing causes at the third. Coupling factors are illustrated as the fourth level of the scenarios. By including all events, the most frequent hazards and causes are captured regardless of consequence.
- The term "human error" is explored and specified in the context of recent fish escape accidents experienced by informants participating in an interview study. Nine organisational and human factors which influence fish escape accidents are identified. The operations associated with increased risk for fish escape are i) net and sinker tube/weight system handling, ii) delousing operations, and iii) vessel-assisted operations. These operations are also associated with elevated occupational risk levels. The findings document a need for increased attention to organisational safety indicators in fish farm operations.
- There is currently no systematic evaluation of operational safety in terms of organisational conditions in the fish farming industry. The OSC method, originally developed for assessment of operational safety levels in the oil and gas industry, has been adapted and evaluated for use in the aquaculture industry. The seven organisational factors from the original OSC are relevant also for fish

farm operations: work practice, competence, procedures and documentation, communication, workload and physical environment, management, and change management.

- The aquaculture industry must comply with regulatory requirements for risk assessments of fish escape, technical condition of fish farms, vessel design and operation, environmental risk, occupational risk, fish welfare and health, and food safety. The current practices differ significantly from the recommended risk assessment procedure on several points. To close the gaps, a new approach which satisfies the requirements is suggested. Risk assessments should be based on the operations carried out at the fish farm. This will provide an overview of the hazards associated with the work tasks and factors influencing the risk levels. The fish farming companies are recommended to develop risk assessment templates for their yearly updates to be adapted to each vessel or fish farm and to ensure involvement of their workers.
- Safety indicators may be useful for monitoring performance related to organisational, operational, and technical safety at the fish farm over time, support decision-making, and detect the need for risk-reducing measures during operations. A six-step method for identification of operational safety indicators is developed and tested. Through application on fish escape event data, forty safety indicators of acceptable quality are identified.

In conclusion, the thesis provides recommendations for practical safety management procedures and approaches which the aquaculture industry may implement in their daily operations and training of new personnel. The results include novel knowledge about the factors and conditions that influence the risk of fish escape during fish farm operations. The fish escape scenarios may be used to improve the reporting system and accident investigations. A holistic understanding of the framework conditions of the fish farms as a workplace and a production site is needed to develop management systems which efficiently capture and manage safety hazards.

LIST OF PUBLICATIONS

ARTICLES IN PHD THESIS (PART II)

1. Journal article:

Yang, X., Holmen, I. M., & Utne, I. B. (Under review). Fish escape data and scenario analysis of Norwegian sea-cage salmon and trout aquaculture.

2. Journal article:

Thorvaldsen, T., Holmen, I. M., & Moe, H. K. (2015). The escape of fish from Norwegian fish farms: Causes, risks and the influence of organisational aspects. *Marine Policy,* 55, 33-38. doi:http://dx.doi.org/10.1016/j.marpol.2015.01.008

3. Conference article:

Holmen, I. M., Utne, I. B., & Haugen, S. (2017). Organisational safety indicators in aquaculture – a preliminary study. In *Risk, Reliability and Safety: Innovating Theory and Practice: Proceedings of ESREL 2016* (Glasgow, Scotland, 25-29 September 2016) (pp. 1809-1816): CRC Press.

4. Journal article:

Holmen, I. M., Utne, I. B., & Haugen, S. (2018). Risk assessments in the Norwegian aquaculture industry: Status and improved practice. *Aquacultural Engineering*, 83, 65-75. doi:https://doi.org/10.1016/j.aquaeng.2018.09.002

5. Journal article:

Holmen, I. M., Utne, I. B., & Haugen, S. (2021). Identification of safety indicators in aquaculture operations based on fish escape report data. *Aquaculture*, 544, 737143. doi:https://doi.org/10.1016/j.aquaculture.2021.737143

DECLARATION OF AUTHORSHIP

The contributions of the candidate and co-authors are presented according to the criteria:

1. Research concept and plan
2. Data collection
3. Data analysis
4. Manuscript drafting
5. Manuscript critical review

Author	Article 1	Article 2	Article 3	Article 4	Article 5
I.M. Holmen	1-5	1, 2, 3, 5	1-5	1-5	1-5
I.B. Utne	5		1, 5	1, 5	1, 5
S. Haugen			5	1, 5	1, 5
X. Yang	1-5				
T. Thorvaldsen		1-5			
H.K. Moe		1, 2, 3, 5			

OTHER SCIENTIFIC CONTRIBUTIONS TO SAFETY RESEARCH IN FISH FARMING

This section presents publications that are not included in the PhD thesis but which contribute significantly to the knowledge foundation regarding safety in Norwegian fish farming operations. These are co-authored journal papers and scientific reports related to contract research projects and associated research activities which I have participated in before and during the PhD project period. The list is organised as follows: title of project, information on funding source, years of duration, list of publications.

Human factors and escape of farmed fish

Research project funded by the Norwegian Seafood Fund (2012-2014), project no. 900835.

This project was the main basis for article 2 (Thorvaldsen et al., 2015).

<u>Scientific reports:</u>

Thorvaldsen, T., Holmen, I. M., & Moe, H. K. (2013). Human factors and escape from sea-based salmon farms. (In Norwegian). SINTEF report series, A2408.

Holmen, I. M., & Thorvaldsen, T. (2015). Good safety work - examples from several industries. (In Norwegian). SINTEF report series, A26675.

Sustainfarmex – towards sustainable fish farming at exposed marine sites

Sustainfarmex laid the scientific foundation for SFI Exposed. This was a knowledge-building project with industry participants supported by the Research Council of Norway (2012-2015). Professor Ingrid B Utne and I were responsible for the safety work package. PhD Siri M Holen was employed as a PhD candidate in this project, and she defended her thesis in 2019 (Holen, 2019), supervised by professor Utne.

<u>Scientific report:</u>

Holmen, I. M., Salomonsen, C., Thorvaldsen, T., & Holen, S. M. (2018). Recommendations for safe workplaces in fish farming (In Norwegian). SINTEF report series, 2018:00096.

<u>Articles:</u>

Holen, S. M., Utne, I. B., & Holmen, I. M. (2014). A preliminary accident investigation on a Norwegian fish farm applying two different accident models. Paper presented at the Probabilistic Safety Assessment and Management PSAM. Honolulu, Hawaii.

Holen, S. M., Utne, I. B., Holmen, I. M., & Aasjord, H. (2018). Occupational safety in aquaculture – Part 1: Injuries in Norway. Marine Policy, 96, 184-192.

Holen, S. M., Utne, I. B., Holmen, I. M., & Aasjord, H. (2018). Occupational safety in aquaculture – Part 2: Fatalities in Norway 1982–2015. Marine Policy, 96, 193-199.

MarinSim – development of a training simulator for fish farm operations

Innovation project for the industry supported by the Research Council of Norway (2013-2018) (grant no. 226561). The project was owned by the Maritime Safety Training Centre in Rørvik, and I was the project manager for the R&D activities.

Article:

Holmen, I. M., Thorvaldsen, T., & Aarsæther, K. G. (2017). Development of a simulator training platform for fish farm operations. Paper presented at the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering.

SFI Exposed - exposed aquaculture operations

Centre for research-based innovation supported by the Research Council of Norway (2015-2023) (grant no. 237790) and hosted by SINTEF Ocean. This PhD project is a part of the research area safety and risk management in SFI Exposed. I was the research manager for this research area from 2015-2019. In addition to this thesis, the following scientific publications are a result of the research within this centre:

Articles:

Bjelland, H. V., Føre, M., Lader, P., Kristiansen, D., Holmen, I. M., Fredheim, A., . . . Schjølberg, I. (2015). Exposed aquaculture in *Norway: Technologies for robust operations in rough conditions*. In OCEANS'15 MTS/IEEE Washington, Washington DC, 19-22 October, 2015 (pp. 10): IEEE conference proceedings.

Utne, I. B., Schjølberg, I., & Holmen, I. M. (2015). Reducing risk in aquaculture by implementing autonomous systems and integrated operations. In E. Zio, L. Podofillini, W. Kroger, B. Sudret, & B. Stojadinovic (Eds.), *Safety and Reliability of Complex Engineered Systems*. (25th European Safety and Reliability Conference, ESREL 2015 ed., pp. 3661-3669). London: Taylor & Francis Group.

Holmen, I. M., Utne, I. B., Haugen, S., & Ratvik, I. (2017). The status of risk assessments in Norwegian fish farming. In *Safety & Reliability, Theory and Applications* (pp. 1457-1465): CRC Press.

Safer operations and workplaces in fish farming

Researcher project granted by the Research Council of Norway (2016-2019) (grant no. 254899). This project focused on the health, safety, and work environment for fish farm operators, safety management, and design of safe workplaces. I was responsible for the application and have participated in the project as a researcher.

Scientific reports:

Thorvaldsen, T., Holmen, I. M., & Kongsvik, T. (2017). Self-reported status of health, safety and work environment in Norwegian fish farming – a survey in year 2016. (In Norwegian). SINTEF report series, OC2017 A-113.

Kongsvik, T., Holmen, I. M., Rasmussen, M., Størkersen, K. V., & Thorvaldsen, T. (2018). Safety management in fish farming. A survey among management and staff (In Norwegian). NTNU Social Research report.

Salomonsen, C., Thorvaldsen, T., Bjelland, H. V., & Holmen, I. M. (2019). Safe design in aquaculture - Design strategies, status and recommendations for product design that safeguards employees' health and safety. SINTEF report series, 2019:00574 A.

Articles:

Kongsvik, T., Thorvaldsen, T., Holmen, I. M., & Størkersen, K. V. (2018). Safety climate and compliance in the Norwegian aquaculture industry – employees' perceptions at different company levels. In S. Haugen, A. Barros, C. van Gulijk, T. Kongsvik, & J. E. Vinnem (Eds.*), Safety and Reliability–Safe Societies in a Changing World* (pp. 157-164): CRC Press.

Kongsvik, T., Thorvaldsen, T., & Holmen, I. M. (2019). Reporting of Hazardous Events in Aquaculture Operations – The Significance of Safety Climate. *Journal of Agromedicine*, 1-10. doi:https://doi.org/10.1080/1059924X.2019.1640818

Kongsvik, T., Dahl, Ø., Holmen, I. M., & Thorvaldsen, T. (2019). Safety climate and health complaints in the Norwegian aquaculture industry. *International Journal of Industrial Ergonomics*, 74, 102874. doi:https://doi.org/10.1016/j.ergon.2019.102874

Thorvaldsen, T., Kongsvik, T., Holmen, I. M., Størkersen, K., Salomonsen, C., Sandsund, M., & Bjelland, H. V. (2020). Occupational health, safety and work environments in Norwegian fish farming - employee perspective. *Aquaculture*, 524, 735238. doi:https://doi.org/10.1016/j.aquaculture.2020.735238

Thorvaldsen, T., Størkersen, K., Kongsvik, T., & Holmen, I. M. (2021). Safety management in Norwegian fish farming: Current status, challenges, and further improvements. *Safety and Health at Work*, 12(1), 28-34. doi:https://doi.org/10.1016/j.shaw.2020.08.004

Sandsund, M., Wiggen, Ø., Holmen, I. M., & Thorvaldsen, T. (2022). Work strain and thermophysiological responses in Norwegian fish farming — a field study. *Industrial Health*, advpub. doi:10.2486/indhealth.2020-0259.

Reducing risk in aquaculture – improving operational efficiency, safety, and sustainability

Researcher project granted by the Research Council of Norway (2016-2019) (grant no. 254913). Project managed by Prof. Ingrid B. Utne, NTNU IMT.

Articles:

Utne, I. B., Schjølberg, I., Holmen, I. M., & Bar, E. M. S. (2017). Risk management in aquaculture: Integrating sustainability perspectives. Paper presented at the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim.

Yang, X., Utne, I. B., & Holmen, I. M. (2020). Methodology for hazard identification in aquaculture operations (MHIAO). *Safety Science*, 121, 430-450. doi:https://doi.org/10.1016/j.ssci.2019.09.021.

Guest editor for the special issue "Safety at Sea," *Journal of Safety Science*:

Bye, R. J., Holmen, I. M., & Størkersen, K. V. (2021). Safety in marine and maritime operations: Uniting systems and practice. *Safety Science*, 139, 105249. doi:https://doi.org/10.1016/j.ssci.2021.105249.

Professional journals, feature articles, and conference presentations:

Dissemination of research results and new knowledge has been important in all research activities to reach the target group of employees in the industry. During the years of my PhD work, I have contributed to several newspaper articles on the topic of occupational accidents and preventive actions in the fishing and fish farming industries, giving interviews, and provided updated analyses of occupational injuries and fatalities. I have also attended several seminars and conferences where I have presented research on different safety topics in fish farming.

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Part I Main report

1 INTRODUCTION

1.1 KEY FIGURES OF NORWEGIAN AQUACULTURE

Norway is the largest producer and exporter of farmed Atlantic salmon and rainbow trout worldwide (FAO, 2020). The total biomass of farmed seafood was 1.5 mill tons in 2020, consisting of 99.6% salmon and trout (Directorate of Fisheries, 2020). Salmon farming alone amounted to 93% of seafood production. A comparison between the five largest salmon farming countries (Canada, Chile, Faroe Islands, Norway, and the UK) shows that the Faroe Islands has the lowest production costs, feed conversion ratio (kg feed/kg harvested salmon), and production losses and the highest smolt yield (amount of harvested salmon/number of smolts released) during the last decade (Iversen et al., 2020). Norway is number two during most of the years included in the analyses, demonstrating that the industry has profitable conditions in Norway.

Norway has a successful tradition of exploiting the nature-given resources for harvesting and farming seafood and is the world's second largest exporter of fish after China (FAO, 2020). Seafood, in particular farmed fish, is the second largest contributor to the export value of goods from Norway after oil and gas. In 2020, Norway exported seafood worth 105.7 billion NOK, and 70% of the export value was farmed fish. The foreign trade of farmed fish alone equals a share of 10% of Norway's total export of goods (778 billion NOK) (Norwegian Seafood Council, 2021; Statistics Norway, 2021). The petroleum industry holds currently 42% of the export value but will eventually decrease. The government consequently appointed the oceans as the main contributor to the nation's future prosperity (Ministry of Trade and Fisheries, 2017a).

The ripple effects of fish farming are significant in a national context. The aquaculture value chain consists of breeding, hatcheries, grow-out production of fish and other aquaculture species (molluscs and algae), processing of seafood, and export activities. The entire value chain employs approximately 12,200 person-years. The ripple effect is calculated to be between 24,000–29,000 person-years, i.e., each person-year in the aquaculture value chain is the basis for 2.4 person-years in other sectors. The contribution to GNP, ripple effects added, was 69 billion NOK in 2019 (Johansen et al., 2020).

Aquaculture production is a significant provider of employment in coastal areas, with close to 10,000 employees, thus surpassing the number of full-time fishers (9,504 in 2020). Fish farming employs approximately 7,100 persons, equivalent to 5,670 person-years. There are 162 fish farming companies in Norway with grow-out production at 986 sites (Directorate of Fisheries, 2020).

1.2 FISH FARM TECHNOLOGY AND OPERATION

The dominant fish farm technology is floating net pens, mainly situated in coastal areas. The farm location and design, structures and components, available equipment, and work vessels, combined with environmental exposure, constitute the physical constraints of the marine operations at the fish farm. Figure 1 shows a salmon-producing fish farm. The typical salmon farm consists of a feed barge (upper right corner) and ten to twelve net cages containing a maximum of 200,000 salmon in each as regulated by the aquaculture production regulation (Ministry of Trade and Fisheries, 2018b). The number of cages is decided by the total amount of fish allowed according to site quality and the production licence, measured in terms of maximum total biomass allowed (MTB) (Hersoug, 2021). Figure 1 has captioned half of the net cages at a particular fish farm outside the coast of Trøndelag, Norway. Modern feed barges are the central operations of the fish farm and have feed silos, stores for equipment, a workshop for repairs, offices and accommodation for workers, and important functions regarding emergency preparedness (Misund et al., 2020). Each fish farm has a staff of three to six workers and an operations manager responsible for both production and personnel safety. One generation of fish is normally grown in the sea-based net pens for eighteen months before harvesting.

Flexible net cages, as seen in the fish farm in Figure 1, are the most common type used in Norwegian fish farming. There are also other flexible net designs, shaped like cones or rectangles. The net cages are kept floating by a double collar of polyethylene tubes. The net cages are kept submerged by a bottom weight system, which may consist of a circular sinker tube and a weight attached to the bottom of the net. The bottom weight is integrated with the stretching system to keep the volume cylindrical. The floater, with its attached handrail and gangway, also supports the circular opening of the net cage. These parts are interconnected with one another with vertical ropes used to lift the bottom weight system during fish crowding. The net cages may be up to one hundred metres across the circular opening and thirty-five metres deep. Each net cage is attached inside a grid of mooring ropes, which is anchored to the sea-bottom or to a nearby rock if available. This flexible system is highly resistant to the constant exposure from hydrodynamic forces, but, due to biofouling, wear and tear, and possible chafing due to environmental forces, regular maintenance is recommended to keep the net barrier and stretching system in good condition.

The fish are fed through feeding tubes, which can be seen in Figure 1 as white lines. Feeding is operated either from the control room at the barge or remotely from shore. Fish feeds are transported to the fish farms by feed vessels. In earlier times, the feed was delivered in huge sacks of 500 kg each. At present, the feed vessels typically deliver feed without involving the personnel at the fish farm and use DP systems to come alongside the barge and transfer the feed through tubes directly into the feed silos.

Figure 1 A conventional Norwegian salmon farm (Photo by SINTEF Ocean and Maritime Robotics, Sensodrone project).

An aquaculture service vessel can be seen in the upper-middle part of the picture (Figure 1). These designated work vessels, which are eight to fifteen metres in length overall (l.o.a.), are used for daily operations and maintenance at the fish farm according to regulations. They typically have capstans, a winch, and/or a crane on board to assist with heavy lifting. The workers at the fish farm are responsible for daily feeding and monitoring the welfare of the fish, removal of mort and visual checks of the condition of the fish farm, and weekly lice counting. These are core tasks to ensure healthy and thriving fish. During the last ten years, the fish farming industry has moved towards an outsourcing of the complex marine operations, involving high-energy interaction with components below the surface, to external service companies. These companies offer specialised, larger service vessels of twenty-four-metre length or more, equipped for heavy operations and with marine crews experienced with these operations. These vessels are chartered for maintenance of moorings, net replacements, and performing or assisting delousing operations, which are associated with increased accident risks (Holen et al., 2018b; Føre and Thorvaldsen, 2021). Wellboats are also frequently used for delousing, in addition to their core functions for fish sorting, transfer, and transport (see Figure 2).

1.3 Sustainability challenges

The Norwegian fish farming industry faces major sustainability challenges. The industry is claimed to be a threat to the environment and in particular to wild salmon due to fish escape (Grefsrud et al., 2019) and parasites or "salmon lice" (Misund, 2019). Moreover, lice counts are now an indicator for the government's regulation of growth in the fish industry, the so-called "traffic light system" (Kristoffersen et al., 2018). Today's aquaculture farms already operate at the safety limit of available technology and personnel. The occupational accident rate in Norwegian aquaculture is the second highest after the fishing industry (Holmen and Thorvaldsen, 2018). This has resulted in a reputation problem for the industry (Olsen and Osmundsen, 2017), which stands in striking contrast to the significant contribution to its national value creation.

Coastal fish farming experience conflicting interests with the protection of wild salmon, the tourist industry, fisheries, other sea-related trades, as well as the public use of the coastline for leisure activities. Due to these conflicts, and since communities have not gained the benefits they expected from the industry, the local authorities are becoming more restrictive in allowing the establishment of new fish farms, with the consequence being a lack of good production sites near-shore (Hersoug, 2021). Furthermore, the increase in production licences for farmed fish have stagnated due to environmental constraints—in particular the lice combat (Ministry of Trade and Fisheries, 2015a).

The government has recently launched an aquaculture strategy which addresses these challenges and aims to lay the groundwork for sustainable growth in aquaculture production (Ministry of Trade and Fisheries, 2021a) in accordance with the UN's sustainable development goals (United Nations, 2016). To enable growth, the environmental impact must be reduced, and more space is therefore sought in more exposed coastal and ocean areas. Conventional fish farm technology is, however, not dimensioned for the tough environmental conditions in areas with little or no shelter. Moving fish farming to exposed areas subsequently requires considerable research efforts and industrial investments to develop new technology concepts (Bjelland et al., 2015). These include novel farm designs and structures matching the increased sea loads, autonomous technology for remote operation and monitoring, and novel vessel designs to ensure sea-keeping abilities and service regularity in shorter operating windows. More importantly, fish welfare must be secured, as well as the safety of fish, workers, and assets.

1.4 WHAT IS EXPOSED AQUACULTURE?

Exposed aquaculture has yet no specific definition. The informative Annex A in the technical standard NS 9415:2009 gives criteria for classification of fish farming sites in terms of wave and current classes (Standard Norway, 2009) (see Table 1). However, these are not connected to established operational limits and are currently only used for classification during site surveys. The wave and current classes are not included in the recent update of the standard (Standard Norway, 2021a).

Table 1 Wave and current classes for classification of fish farming sites from the informative Annex A in NS 9415:2009 (Standard Norway, 2009).[1]

Designation	Wave classes	Significant wave height H_s (m)	Wave period T_p (s)	Current classes	Midcurrent V_c (m/s)
Little exposure	A	0.0–0.5	0.0–2.0	a	0.0–0.3
Moderate exposure	B	0.5–1.0	1.6–3.2	b	0.3–0.5
Substantial exposure	C	1.0–2.0	2.5–5.1	c	0.5–1.0
High exposure	D	2.0–3.0	4.0–6.7	d	1.0–1.5
Extreme exposure	E	>3.0	5.3–18.0	e	>1.5

The potential for sustainable offshore aquaculture is being explored worldwide (FAO, 2020). As for exposed aquaculture, no established definition exists. A common definition of offshore fish farming would establish a comparable framework for R&D between countries and also support regulatory processes globally (Froehlich et al., 2017). Holmer (2010) presented definitions of coastal, off-coast, and offshore farming based on distance from shore and water depth; exposure in terms of waves, winds, and currents; and legal definitions (within coastal baseline, national or international waters). Chu et al. (2020) reviewed Holmer's definition and other suggestions from the research community and found an agreement on a set of parameters associated with offshore fish farming. Accordingly, the authors suggested the following definition: i) unsheltered sites, at least three kilometres from shore but within an exclusive economic zone (EEZ), ii) water depth >50 m or more than three times the cage height, at least fifteen metres between cage bottom and seabed, iii) water current speed 0.1–1 m/s, and iv) and wave height above three metres. This falls within the wave class E (extreme exposure) in Table 1.

The Norwegian ambition of multiplying aquaculture production has initiated efforts to explore the possibilities of offshore fish farming. The government addresses regulatory issues associated with moving aquaculture production farther from shore in the report "Offshore Aquaculture" (Ministry of Trade and Fisheries, 2018a). The sea areas within Norwegian EEZs are classified into inshore waters, open waters, and outer waters, and the latter two apply for "offshore aquaculture." Only inshore waters are covered by today's regulations for aquaculture area permits. In addition, issues regarding aquaculture activity in international waters are discussed. Mobile farms may move between the different areas, and hence another regulatory challenge is raised.

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[1] Table 1 - Wave and current classes for classification of fish firming sites from NS 9415:2009 is reproduced by I.M. Holmen in the doctoral thesis "Safety in Exposed Aquaculture Operations" under licence from Standard Online AS November 2021 (c). All rights are reserved. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. In any case of dispute, the Norwegian original shall be taken as authoritative. See www.standard.no.

Exposed aquaculture, however, cannot be solely categorised by physical parameters, distance from shore, or dimensioning of structures according to sea loads. Farming of fish involves living animals, and humans are needed for taking care of the fish. A decade ago, there were particularly rough conditions during the winter of 2011–2012. An interview study was conducted to collect the fish farmers' experiences. The study concluded that, during periods of reduced availability of the fish farms, the monitoring of fish welfare and the fish farm technical state could not be conducted in accordance with the regulatory requirements (Thorvaldsen et al., 2013). Fish feed deliveries and wellboat operations were postponed, as well as maintenance of components and structures. The fish mortality rate increased, as well as the risk of fish escape. Furthermore, the workers' occupational safety was sacrificed in attempts to do the mandatory daily checks (Holen et al., 2013). Aquaculture production in exposed areas may result in more frequent periods of reduced availability for regular maintenance and vessel operations at the fish farm, general harsher working environments, and increased threats to fish welfare. The emerging risks associated with fish farming under these conditions need to be systematically assessed and managed.

1.5 Future offshore aquaculture

A wide range of fish farm concepts have been developed globally. There are open, semi-closed, and closed fish net cage and tank designs (Chu et al., 2020). One of the greatest challenges with today's dominating design in Norwegian water, open floating and flexible cages, is that strong currents deform the shape of the net cage. Furthermore, moorings and stretching system components may chafe the net and cause holes. Manufacturers have improved this design for more exposed sea conditions. However, these fish farms need to be anchored with lines three to five times the water depth and are therefore not suitable for increased water depths offshore.

The so-called development licences are a time-limited scheme launched by the Norwegian authorities in 2015 to encourage innovation of novel sea-based fish farm production concepts requiring significant investments (Directorate of Fisheries, 2018b). The aim of the scheme is to solve one or more of the environmental and area challenges experienced by the fish farming industry and is an innovation driver for exposed aquaculture. No payment is requested, and the companies may apply for the development licences to be converted into ordinary fish farming licences after some production time if a set of criteria approved for each project is fulfilled (Hersoug et al., 2021). The design shall be documented to support reduced environmental impact of fish farming and must be dimensioned according to the conditions of the future location.

104 applications were received within the deadline in November 2017. As of September 2021, twenty-three development licence projects have been granted (a few are already set into production), seventy-eight declined, and three are still pending (Directorate of Fisheries, 2021a). The development licences scheme will result in a variety of new fish

farm concepts (Directorate of Fisheries, 2021c). The operations, as we know them in conventional fish farming, need to be adapted to new components, equipment, and workplace arrangements. Introducing new technology concepts may introduce new types of risk for failures and harm to workers and fish (Swuste et al., 2020). Furthermore, several of the new constructions are considerably bigger than the conventional fish cages. Hazardous events may subsequently result in major accidents in terms of large-scale fish escapes, injuries/fatalities, or considerable material damage (Holen et al., 2019).

1.6 Risks in fish farming

Yang et al. (2020) defined five dimensions of risks for the operation of Norwegian fish farms: risk to material assets, personnel, fish welfare and health, environment, and food safety. These dimensions are further described in this section.

Food safety is protected by strict regulations for control of the residues in the fish meat due to any treatment agent applied to the fish for bacteria or parasites. Although still used, the use of anti-lice agents has decreased in Norway; studies show, however, compliance well within the with maximum residue limits set by the EU (Hannisdal et al., 2020). Due to a low level of bacterial infections in Norwegian farmed fish, antibiotics are used in very small amounts over several years and hence not regarded as a risk to food safety (Grefsrud et al., 2018).

The ongoing battle against sea lice increases the production cost as well as fish mortality (Iversen et al., 2017; Iversen et al., 2020). New ways of parasite treatment have been developed which also introduce new hazards to the fish welfare and health due to a tough treatment of either chemicals, warm water, or mechanical "brushing" (Grefsrud et al., 2018; Overton et al., 2018). The sea lice treatments are directly related to Atlantic salmon mortality (Oliveira et al., 2021). In 2018, the overall mortality of farmed Atlantic salmon in Norway was 15.8%, which is the consequence of welfare hazards due to stress, disease, injuries, or parasites (Bang Jensen et al., 2020). Moving fish farming to offshore locations may reduce the problems due to parasite risk and coastal area conflicts, but the exposed living conditions may be too tough for the farmed salmon to thrive and hence be a risk to fish welfare (Hvas et al., 2021). Cleaner fish used for biological delousing endure less exposure than the salmon, and a study has shown losses of the cleaner fish ballan wrasse up to 58% after four months in fish cages (Geitung et al., 2020). Hence, fish welfare is challenged both for farmed salmon and cleaner fish.

Fish escape is associated with fish welfare and environmental risk. Fish escape is also a risk in terms of economic loss. Given a net profit of twelve NOK per kg of salmon (Directorate of Fisheries, 2020), an escape of 100,000 salmon ready for slaughter (approximately five kg/each) would equal an economic loss of 6 million NOK. During the last decade, the industry has accomplished a great reduction in the number of fish escape incidents caused by technical failures in constructions and equipment (Føre and

Thorvaldsen, 2021). The overall aim of the industry, however, is zero escapes, and thus authorities continue their regulatory focus on prevention of fish escapes (Ministry of Trade and Fisheries, 2017b).

Fish farming involves the risk of damage to material assets. Production of seafood at sea is heavily dependent on the use of vessels for different purposes: boats for transport of workers, work vessels, service vessels, wellboats, and feed vessels. Manoeuvring inside the mooring grid and between fish cages introduces hazards to the structures and components of the fish farm. Mooring lines may break due to forces from the vessels and cause breakdowns of the net cages, vessels may collide with the net cages and cause escapes due to submergence of the floaters, and the wellboat thrusters or vessel propellers may cause damage to the net (Yang et al., 2020). Environmental forces may also be a hazard to fish farms. In February 2021, a fish farm in Northern Norway was hit by an avalanche (Nygård and Njåstad, 2021). Gales and high waves may cause serious deformation of fish farms, as happened at the Faroe Islands in 2017 (Berthelsen, 2017).

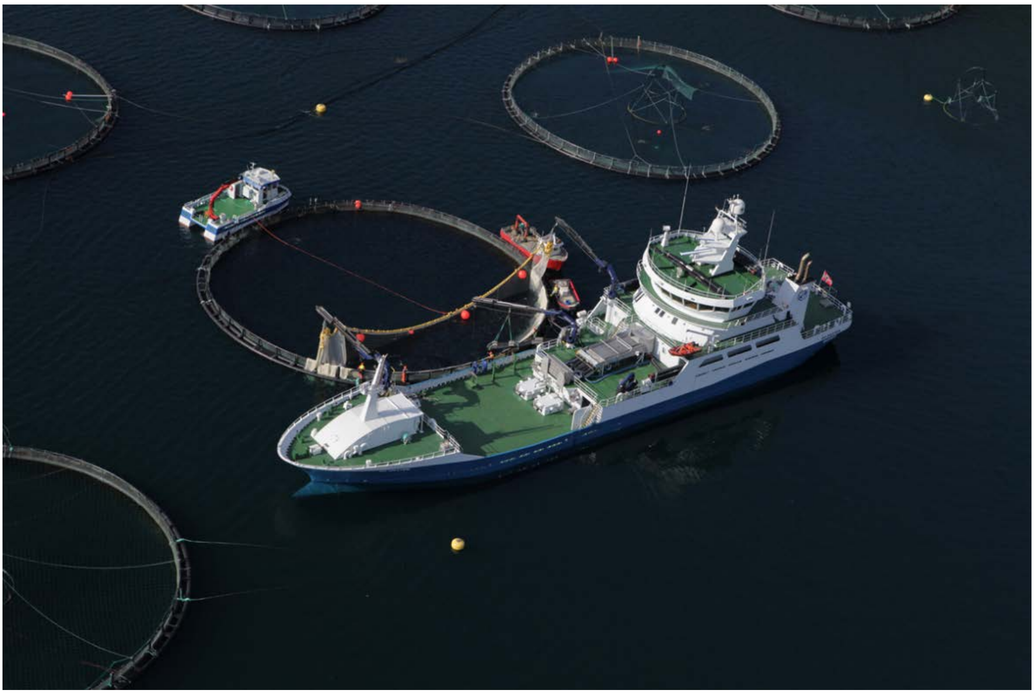


Figure 2 A fish crowding and sorting operation. (Picture reproduced with permission from Rostein AS.)

Seafood production in open waters introduces risk to the environment. As mentioned previously, the spread of lice and diseases and mixing of genes from escaped salmon threaten wild salmon stocks. The use of chemical treatments may release agents into the sea which are toxic for wild marine species (Grefsrud et al., 2019). There is also a risk for environmental impacts in a longer term, e.g., organic waste emissions and negative effects of sediments on benthic biodiversity (Holmer, 2010). Although not a direct risk to fish farmers and farmed fish, these risks should be included in a holistic safety management perspective.

Nature has also the potential to "strike back" and be a risk to the fish. Harmful algae blooms may be a threat to the farmed fish and other seafoods harvested (Karlson et al., 2021). Increased sea temperatures may also kill fish in net cages due to a decrease in oxygen levels inside the cages caused by an unfavourable combination of conditions, such as shallow net pens, high density of fish, and inadequate waterflow through the net pens (Calado et al., 2021). When this happens, it is urgent to move the fish from the affected areas and to remove already dead fish to prevent breakdown of the fish cages and escape of the still-living fish. These operations require resources which might not be readily available at the fish farms. Experience from the harmful algae bloom in Northern Norway in 2019 showed that operations go around the clock and extra crews are needed. Extra resources are also needed, e.g., wellboats, pumps, assisting vessels to transport fish, and vessels to tow net cages to clean fjords (Karlsen et al., 2019). These massive mortality events may not be possible to mitigate, hence efforts are initiated to develop monitoring systems which give the fish farmers a warning of toxic algae blooms or sea water temperatures increasing above normal levels.

Salmon lice levels, by decree, must be monitored closely (Ministry of Trade and Fisheries, 2016b). The results are public and are updated online on a weekly basis (BarentsWatch, 2021). The national requirement instructs that delousing shall be initiated if there is more than 0.5 louse per fish on average in a fish farm. Some companies have stricter internal rules and may delouse single cages at the 0.1 level. There is a strong incentive for this, as fish farms which document under 0.1 mature female lice per fish may apply for an increased MTB, and this can be granted independently of the colour of the traffic light system in the home region of the fish farm (Thorvaldsen et al., 2019).

The aquaculture regulation requires regular monitoring of parameters related to the health and welfare of the fish. These are water quality, oxygen levels, density of fish, and general wellbeing (Ministry of Trade and Fisheries, 2018b). The health risk is highest during the treatment, transfer, and transport of fish. Any event compromising the health of the fish shall be reported to the Food Safety Authority. The fish farms have cameras immersed in the fish cages for monitoring fish behaviour and feeding, and experienced operators assess the fish daily by visual observations. Daily removal of mort is mandatory, and the amount is recorded because it is an indicator for overall fish welfare. These risks to fish welfare and health need to be included in risk assessments, and emergency preparedness has to be dimensioned to mitigate hazardous events.

The rate of occupational injuries has decreased in terms of the number of registered injuries related to the number of person-years employed (Holen et al., 2018a). Undesired events and fatal accidents, however, still happen at an unacceptable level (Holen et al., 2018b; SINTEF Ocean, 2020). Previous research studies conclude that potentials exist for improving occupational safety both in Nordic fish farming (Holen, 2019; Kaustell et al., 2019) and the aquaculture industry globally (Moreau and Neis, 2009; Myers and Durborow, 2012; Mitchell and Lystad, 2019; Ngajilo and Jeebhay, 2019; Watterson et al., 2019; Ochs et al., 2021).

Furthermore, environmental forces may negatively influence the performance of operations. Fish farms are located at sea and are exposed to all kinds of weather, such as exposure to wind, waves, and currents. Figure 2 shows a delousing operation. It involves one workboat and two service vessels assisting in the crowding of fish, which are pumped into the wellboat tank for treatment. On this day, the weather was nice and the sea calm. However, a deterioration of weather conditions would worsen the operating conditions dramatically. The experience of the fish farmers reflects that bad weather and darkness increase the risk for accidents (Holen et al., 2013). During interviews, the fish farmers have been asked, "What is bad weather?" The answer to this is never straightforward. The answers are usually a combination of wind direction and speed, wave heights, and tidal currents (Thorvaldsen et al., 2015). Other factors might be precipitation in combination with low temperatures and unfavourable wind directions that cause icing (Yang et al., 2020). In the future, more remote and exposed locations could exacerbate the risk picture due to the stronger impact of environmental factors.

Considering the risk dimensions and the seriousness of the potential consequences of accidents, the following question was raised: How well does the aquaculture industry manage existing and new hazards to prevent hazardous events and mitigate accidents? There seemed to be a need for a review of the fish farming industry's safety management practices according to the current regulatory requirements and for a systematic analysis of factors and conditions influencing operational risk levels in fish farming. Furthermore, the range of potential risks implicates a need for holistic risk assessments which capture new hazards emerging from implementation of new fish farm concepts and technologies and seafood production at more exposed locations.

1.7 Objectives

The main objective of this PhD project is to develop knowledge and methods for improved safety management in exposed sea-based fish farming.

The project activities have been designed according to five research objectives:

1. Analyse fish escape event data and identify hazards and fish escape scenarios which may develop into hazardous events.
2. Analyse the influence of organisational and human factors in fish escape accidents.

3. Evaluate whether the Operational Safety Condition (OSC) method from the oil and gas industry is applicable to fish farm operations.
4. Explore the status for risk assessment practices in the Norwegian fish farming industry in relation to regulatory requirements.
5. Identify human, organisational, and technical risk-influencing factors and develop safety indicators for reducing risk for fish escape during fish farm operations.

The PhD project has been funded by the Centre for Researched-Based Innovation in exposed aquaculture operations, SFI Exposed, as a part of the safety and risk management research area.[2] SFI Exposed (2015-2023) is based upon a close collaboration between researchers, fish farming companies, service providers to the aquaculture industry, and other industry participants. The overall aim of SFI Exposed is to develop concepts for safe fish farming at exposed production sites. The hypothesis for the safety research in SFI Exposed is that more suitable methods and strategies for risk reduction in aquaculture operations can be developed based on knowledge about the special characteristics of the workplaces and the organisation of safety in this industry.

1.8 Scope and limitations

The scope of the PhD project has been the operational, grow-out phase of sea-based fish farming in Norway. Transport of fish by wellboats or processing of fish in plants onshore have thus not been included. The results are expected to contribute to improved safety management in the fish farming industry, but specific safety management systems as such are not addressed as a separate topic in the research. The targeted audience is fish farmers; safety representatives; health, safety, and environment (HSE) coordinators; production and company managers; regulatory authorities; and the growing global scientific community concerned with safety in aquaculture.

The PhD research has been conducted using fish escape events as the case study. As previously described, aquaculture operations introduce hazards for personnel and increase the risk of material damage and fish escape. Occupational safety may be challenged because workers try to avoid fish escape at the expense of their own safety due to looming reputational risk. Preventing fish escape may hence reduce the overall risk level at the fish farm by maintaining fish welfare, worker's safety, structural integrity, and the possible negative impact on the environment. The developed methods are generic and should be relevant for all risk dimensions associated with aquaculture operations, i.e., for reducing occupational risk, uncontrolled spreading of parasites ("salmon lice"), risk for damages to material assets, and environmental or reputational risk.

[2] Homepage: www.exposedaquaculture.no

Since many of today's fish farms are regarded as exposed in terms of high environmental loads and reduced availability due to harsh weather and challenging sea conditions, most of the work is based on state-of-the-art technology of floating net cage fish farming. The methodological approach for improving operational safety is independent of technological solutions and hence applicable to the novel fish farm concepts which eventually are being set into operation. The results thus provide a basic understanding of the multiple hazards and risk-influencing factors relevant for exposed aquaculture operations.

1.9 Structure of the thesis

The thesis consists of two main parts. Part I, the main report, presents the background for the research, methodology, and a synthesis of the contributions from the research published in articles. The scientific articles are included in Part II.

Part I contains the following chapters. Chapter 1 is an introduction to the Norwegian aquaculture industry and the topic of the thesis and presents the objectives, scope, and limitations of the PhD project. Chapter 2 covers the theoretical background for the research. It starts with an overview of the safety regulations and practices in the Norwegian fish farm industry. The second part of the chapter summarises safety and risk management methods relevant in the context of the aquaculture industry and the PhD project. Chapter 3 places the PhD research in a broader context and discusses the methodology and chosen research design. Chapter 4 presents the main results and how they contribute to the research front, as well as their potential to help improve operational safety in fish farming. Chapter 5 concludes the thesis and recommends future research beyond the present PhD work. References are included in the last section of Part I.

1.10 List of Abbreviations

BN	Bayesian Network
DP	Dynamic Positioning
EEZ	Exclusive Economic Zone
FAO	Food and Agriculture Organization of the United Nations
Fdir	Norwegian Directorate of Fisheries (Fiskeridirektoratet)
GNP	Gross National Product
HSE	Health, Safety, and Environment
IMT	Department of Marine Technology
MTB	Maximum total biomass allowed
NMA	Norwegian Maritime Authority (Sjøfartsdirektoratet)
NAV	Norwegian Labour and Welfare Administration (Arbeids- og velferdsetaten)
NLIA	Norwegian Labour Inspection Authority (Arbeidstilsynet)
NOK	Norwegian Kroner (Currency)
NSD	Norwegian Centre for Research Data, Data Protection Services
NSIA	Norwegian Safety Investigation Authority (Statens havarikommisjon)
NTNU	Norwegian University of Science and Technology (Norges teknisk-naturvitenskapelige universitet)
OECD	Organization for Economic Cooperation and Development
OED	Oxford English Dictionary
OHS	Occupational Health and Safety
OSC	Operational Safety Condition
PhD	Philosophiae Doctor
R&D	Research and Development
RIF	Risk-Influencing Factor
SJA	Safe Job Analysis

2 THEORETICAL BACKGROUND

This chapter provides the theoretical background for the thesis. The first section defines important terms and concepts in safety. Section two gives an overview of the regulatory framework for safe operations and current practices in safety management in the fish farming industry. The remaining parts of the chapter present a theoretical background of methods for assessing safety performance. The emphasis is placed on identification and monitoring of risk-influencing factors (RIFs) in terms of safety indicators and safety performance audits. The knowledge needs for enabling safe offshore aquaculture production concludes the chapter.

2.1 TERMINOLOGY AND CONCEPTS

In the safety research literature, the same terms may be used with slightly different meanings. In this report, *event* is the generic term for all accidents and incidents regardless of consequence and for events that may occur. The following terms are defined according to Rausand and Haugen (2020):

Accident is a sudden, unwanted, and unplanned event or event sequence that has led to harm to people, the environment, or other tangible assets.

Incident is a sudden, unwanted, and unplanned event or event sequence that could reasonably have been expected to result in harm to one or more assets but did not.

Incident is also named *near-miss* in the report. Some professionals within the industry may call this an "undesired event." This is unfortunately inconsistent in the articles, as incident has been used instead of event.

Hazard is a source or condition that alone or in combination with other factors can cause harm.

Hazardous event is an event that has the potential to cause harm.

An *accident scenario* is defined as a potential sequence of events from an initiating event to an undesired end state that will harm one or more assets.

There are several definitions of *risk* in the literature. The international standard on risk management defines risk as "the effect of uncertainty on objectives" (ISO, 2018c). The International Risk Governance Council (IRCG) adopted the risk definition "an uncertain (generally adverse) consequence of an event or an activity with regard to something that humans value" (Graham et al., 2010) based on the original definition by Kates et al. (1985). In this thesis, the definition by Kaplan and Garrick (1981) is used. They defined *risk* as the combined answer to three questions: *1) What can go wrong? 2) What is the* *likelihood of that happening? 3) What are the consequences?* This understanding of risk reflects the phases of risk assessment and is therefore a practical definition to communicate to the sharp-end workers in the fish farming industry.

A risk-influencing factor (RIF) may be explained as any condition influencing risk. In the thesis, the general definition by Rausand and Haugen (2020) is adopted: *"Risk influencing factors are background factors that influence the causes and/or the development of an accident."* The RIFs should ideally cover all aspects of risk influence during an operation, including those that are environmental, organisational, operational, human, and technical (Yang et al., 2017). Human factors refer to environmental, organisational and job factors, and human and individual characteristics which influence behaviour at work in a way which can affect safety levels. Organisational factors are related to management, competence, workloads, compliance with procedures, and more.

Safety is expressed as a function of risk (Rausand and Haugen, 2020): *"A state where the risk has been reduced to a level that is as low as reasonably practicable (ALARP) and where the remaining risk is generally accepted."*

ISO 45001 defines a *management system* as a set of interrelated or interacting elements of an organisation that establish objectives and policies and processes to achieve those objectives (ISO, 2018b). *Risk management* is defined as coordinated activities to direct and control an organisation with regard to risk (ISO, 2018c). The definition by ISO is generic and may be used for several risk dimensions, e.g., financial, environmental, reputational, occupational. Risk management is a set of control tasks of identified hazards and is based on a closed loop feedback, as illustrated in Figure 3.

Safety management concerns the systematic activities that prevent accidents and injuries and manage safety hazards in an organisation. Tools for safety management may be risk assessments, accident investigations, nonconformity reporting, safety indicators, safety audits, and inspections and analyses of accidents and hazardous events (Kjellén and Albrechtsen, 2017). The same tools are used in risk management, which may be regarded as a part of safety management for the risks concerning safety of the production activities in an industry (Li and Guldenmund, 2018). The responsibilities of defined safety functions at workplaces, goals for the safety performance, description of activities, procedures, nonconformity registrations, audits, internal investigations, risk assessments, measures, and more are documented in a *safety management system* (Kongsvik et al., 2018a).

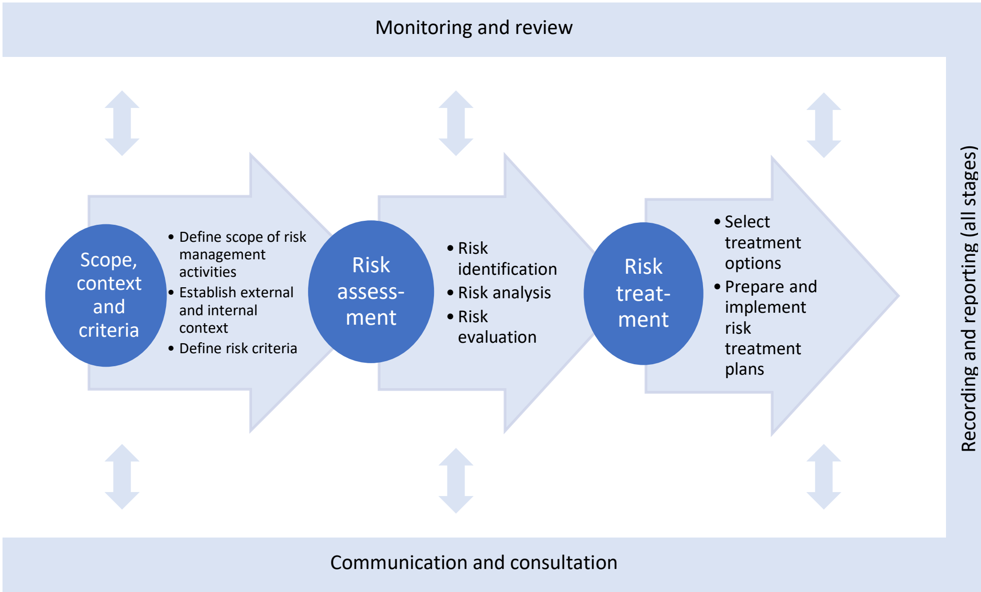


Figure 3 Risk management according to ISO 31000 (ISO, 2018c).[3]

2.2 AUTHORITIES AND STATUTORY REGULATIONS

The primary function of safety management is decision support for applying relevant measures to manage identified risks. Safety management in organisations is directed by framework conditions both within and outside the company (Kjellén and Albrechtsen, 2017). Important internal conditions are the size of the company, organisational structure, safety policies and compliance with regulations, board room and management attention to safety, technology levels, characteristics of the production, geographical span, resources in terms of human competence, and economic capital.

Externally, procedures and requirements applicable for fish farm operations are developed by regulatory authorities, industry standards, and federations, with input from a tripartite cooperation involving industry representatives, worker associations, and regulators (Holmen and Thorvaldsen, 2018).

Figure 4 shows the regulatory framework applicable for fish farm production and operations in Norway. The Norwegian aquaculture production must comply with requirements from seven legislative areas, which are supervised by the following five regulatory authorities: the Directorate of Fisheries (Fdir), the Norwegian Maritime

[3] Figure 3 - Risk management according to ISO 31000 is reproduced by I.M. Holmen in the doctoral thesis "Safety in Exposed Aquaculture Operations" under licence from Standard Online AS November 2021 (c). All rights are reserved. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. In any case of dispute, the Norwegian original shall be taken as authoritative. See www.standard.no.

Authority, the Food Safety Authority, the Labour and Inspection Agency (NLIA), and the County Administration/Governor. Several public bodies are involved before the fish farm receives its production licence due to coastal area management regulations (Robertsen et al., 2016). This part of the governance is outside the scope of the thesis and hence not further described.

A summary of the regulatory framework for safety and risk management in Norwegian fish farming is presented in the following. Safety management systems are governed by the Working Environment Act (Ministry of Labour and Social Affairs, 2005), the Aquaculture Act (Ministry of Trade and Fisheries, 2005), the Food Safety Act (Ministry of Health and Care Services, 2003), and the Animal Welfare Act (Ministry of Agriculture and Food, 2009).

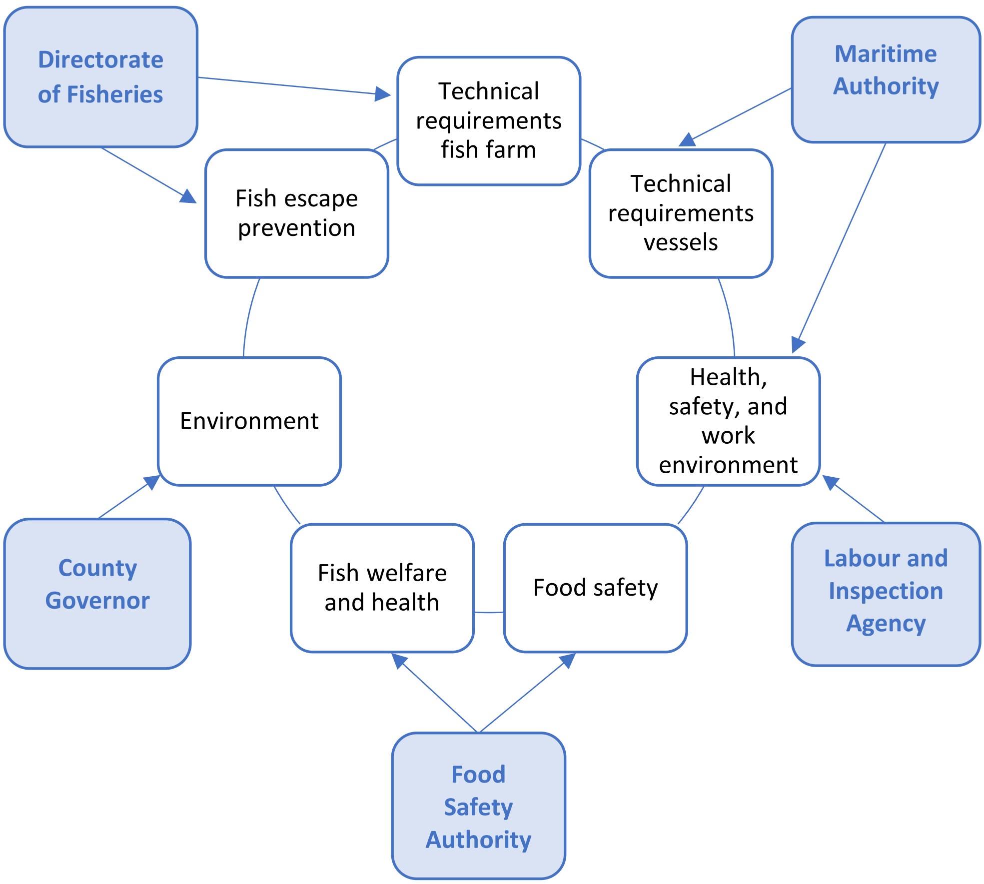


Figure 4 The regulatory framework for safety and risk management in fish farming (grow-out phase). Illustration of the five Norwegian authorities with jurisdiction within seven regulatory areas.

Internal control is mandated by the internal control regulation for HSE (Ministry of Labour and Social Affairs, 1996), which was last updated in 2017. Internal control compliance within aquaculture legislation (Ministry of Trade and Fisheries, 2004) targets the aquaculture production specifically, but the structure is equal to the HSE internal control. Internal control is about systematic actions to ensure that the company's operations are planned, organised, executed, safeguarded, and kept in accordance with the regulatory requirements. The internal control loop is illustrated in Figure 5. The internal control system requires thorough documentation of internal procedures, risk assessments, treatment of nonconformities, internal audits, action plans for preventive work and improvement activities, plans for training of personnel, and involvement of personnel in these activities. It is therefore a basis for safety management in a company.

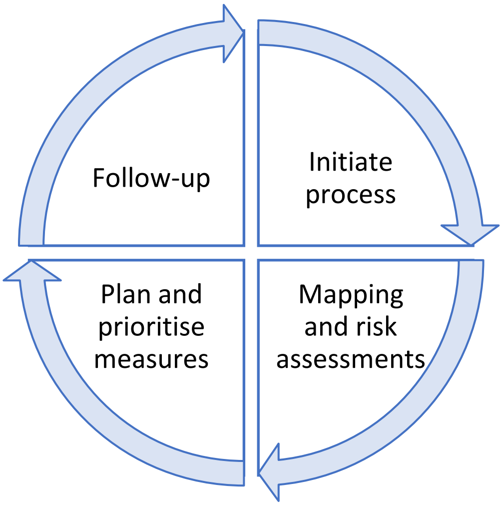


Figure 5 Internal control loop, according to the regulations for internal control (see text).

The "Regulation on the operation of aquaculture production sites" (Ministry of Trade and Fisheries, 2018b) outlines the obligations of fish farmers to prevent escape and report fish escape events and is founded on the Food Act and the Animal Welfare Act, which regulate the welfare and ethics of the farmed fish. The allowed salmon lice levels and requirements for counting, delousing, and regional cooperation are guided by the regulation on salmon lice control in aquaculture facilities (Ministry of Trade and Fisheries, 2016b).

The technical standard NS 9415 (Standard Norway, 2009) is upheld by the "NYTEK regulation" to ensure the minimum technical quality and dimensions of aquaculture installations (Ministry of Trade and Fisheries, 2011). An updated version of NS 9415 was published in August, 2021, and a revised regulation named NYTEK22 is to be implemented January 1^{st}, 2022 (Ministry of Trade and Fisheries, 2021b).

The aquaculture work and service vessels under fifteen metres are required to comply with the regulation on construction and inspection of small cargo ships (Ministry of Trade and Fisheries, 2015b). These vessels were previously not inspected by the Norwegian Maritime Authority. The implementation of the regulation in 2015 changed this, and, in 2017, these vessels were decreed to implement safety management systems on board (Ministry of Trade and Fisheries, 2016a).

In addition to regulations, the government establishes policies and strategies to direct the regulatory authorities' priorities. The government's strategy to prevent fish escape has five priority areas (Ministry of Trade and Fisheries, 2017b): 1) knowledge (including learning from analyses of fish escape events), 2) experience sharing and dialogue (both between authority-industry and between companies), 3) strong safety culture (audits of management systems supporting this will be prioritised), 4) effective regulations (introduce requirements for barrier management and standardisation), and 5) professional emergency preparedness. The Fdir follows up this strategy and has recently initiated a project to develop a guide for holistic risk management systems in the aquaculture industry (Directorate of Fisheries, 2021d). The aim is to establish best practices for risk management in the industry, which actively are used to prevent hazards and undesired events. The risk management system shall be improved continuously. The guide will build upon NS5814 and ISO 31000 and is assumed to cover the requirements of the regulation for internal control in aquaculture, IK-Akvakultur (Ministry of Trade and Fisheries, 2004).

2.3 VOLUNTARY CERTIFICATIONS

The industry has established a practice of being accredited according to a number of international standards—e.g., ISO 9001 (ISO, 2015) and ISO 45001 (ISO, 2018b)—and standards for sustainable aquaculture production—Aquaculture Stewardship Council (ASC), GLOBAL G.A.P. (Good Agricultural Practices), assessed by a third party (Amundsen and Osmundsen, 2020). The certifications work as a means to manage risks but also improve public image as a response to market demands for sustainability (Olsen et al., 2021).

Certification schemes as such are not explored within the scope of the thesis, although the social pillar of sustainability includes requirements for human safety and sound workplaces. However, the Norwegian regulatory approach to maintain safe and healthy work environments is regarded as the best standard globally (Watterson et al., 2019).

2.4 SAFETY MANAGEMENT IN NORWEGIAN FISH FARMING

Implementation and maintenance of a safety management system is mandatory for fish farm companies and aquaculture vessels. Safety performance can be evaluated through measurement of safety barrier quality, safety evaluation programs, or in terms of losses (Øien et al., 2011b). In general, tools for safety management are (Kongsvik et al., 2018a):

- Accident investigations
- Analysis of events reported to the regulatory authority (database of aggregated accidents and incidents)
- Inspections according to regulatory requirements
- Reporting of nonconformities (company internal)
- Risk assessments
- Safety indicators
- Safety performance audits (by authority or third party, or internal control audits)

All these methods have in common that they provide knowledge about the safety performance of the organisation, which is used to implement the necessary measures for hazard control. Investigations of accidents, analyses of accident registrations, and reporting of nonconformities may be a basis for identification of conditions and factors important for the development of the hazardous event and following accident. Risk assessment is a tool to identify hazards associated with, for instance, an operation, a piece of equipment, or a workplace. Knowledge from analyses of accidents and near-misses is valuable input to the risk assessments. Furthermore, inspections and safety audits are performed to check the compliance of the safety procedures and measures, i.e., the success of safety management implementation.

The risk picture and safety levels at the fish farm are likely to be different during periods of normal operation compared to periods of a certain activity, e.g., maintenance operations or fish crowding (Yang and Haugen, 2015). As of today, the risk assessments are related to the risk dimensions and not coupled in one system (Holmen et al., 2017b). This implicates a need for a decision-support tool related to the actual safety levels during marine operations. The operational manager would benefit from a tool objectively assisting decisions during operational planning to help decide if it is safe to start. Furthermore, the tool should also define operational limits during the operation and have abort criteria related to elevated risks for, e.g., fish escape and threats to personnel or fish. Such a tool could be safety indicators which measure the condition of the risk-influencing factors at the fish farm.

The number of fish escape events and occupational accident frequencies may be categorised as safety indicators (cf. section 2.4.8). However, these indicators are not associated with the safety level of future or ongoing operations. They are measures of the consequences of a hazardous event. Lice counts may be argued to be an indicator linked to a future increase in risk levels, because increasing levels may initiate a delousing operation. However, the mandatory measurements of fish welfare indicators, lice infestation, and quantifications of environmental impact do not reflect operational safety.

Table 2 summarises the current methods used for follow-up by the regulatory authorities and third parties and safety management in companies and at each fish farm. The following subsections describes these complementary approaches in more detail.

Table 2 Tools and methods for safety management at the different organisational levels in the fish farming industry.

Organisational level	Authority	Third party	Company	Fish farm
Accident investigations	x		x	
Analysis of events reported to the regulatory authority	x			
Inspections according to regulatory requirements	x	x	x	x
Reporting of nonconformities			x	x
Risk assessments			x	x
Safety indicators	x		x	x
Safety performance audits	x	x	x	x

2.4.1 Accident investigations

Accident models have been designed with the aim to explain why accidents happen, and to identify how to avoid similar accidents. Accident models can be grouped according to their characteristics as follows (Kjellén and Albrechtsen, 2017): 1) "chain of events" or causal-sequence models resulting in a loss, 2) process models based on a theory that deviations from normal conditions result in lost control and injuries, 3) energy models displaying accidents as energy transfer and introducing barriers to protect humans and assets, 4) logic tree models of events and conditions in the system, 5) systemic accident models, and 6) cognitive models focusing on human errors.

Kjellén and Albrechtsen (2017) developed an accident analysis framework based on elements from the process, energy, and systemic accident models (Figure 6). It consists of three main parts: i) input—contributing factors and root causes, ii) process—deviations, incident, energy absorption, and iii) output—type of loss (people, environmental, material assets, reputation). Accordingly, three categories of safety performance indicators may be derived from this model. Indicators may measure the output, e.g., number of injured people, or the process safety performance, e.g., frequency of incidents. The third category of indicators are those derived from causal factors, which may origin from the human, organisational, or technical systems at the workplace. Establishment of safety indicators related to the contributing causes—or early stages of losing control in the process—would be a powerful measure to prevent incidents with potentially serious consequences and hence a good investment for risk management.

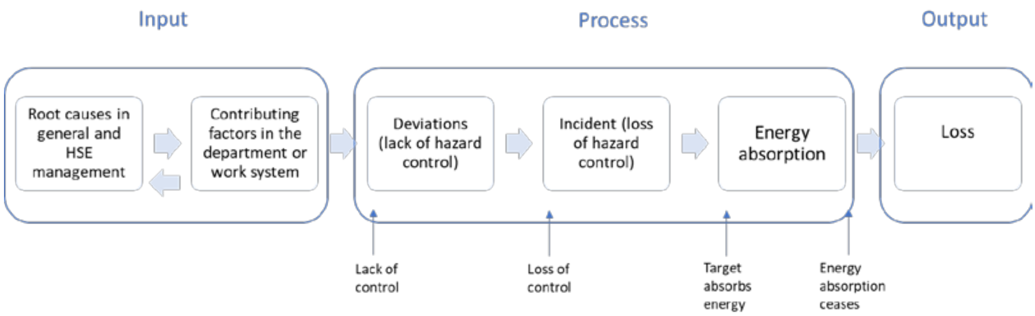


Figure 6 The accident model by Kjellén and Albrechtsen (2017).

Modern industry companies may have a complex organisation to manage to keep pace with technology development as well as changing external conditions and aligning with regulatory boundaries. More recent accident models reflect this by treating safety as a control problem of a socio-technical system and not as linear interactions between its components (Leveson, 2017). The socio-technical system was first presented by Rasmussen (1997) and illustrates that contributing factors on many levels, from the task-specific operational level to regulatory and governmental, should be included in a complete model for risk management. Safety as a control problem in a complex system is also the basis for Leveson's theoretical framework for causal modelling of accidents, STAMP (Systems-Theoretic Accident Model and Processes) (Leveson, 2004), and the STPA (Systems-Theoretic Process Analysis) technique for hazard analysis (Leveson, 2015).

STPA has been applied to develop leading safety indicators in the engineering of safety-critical systems in aircrafts (Leveson, 2015). It was slightly modified and successfully applied to identify safety checkpoints for the control structure at a gas production facility (Yousefi and Rodriguez Hernandez, 2020). Relevant for the topic of this thesis, Holen and Utne (2018) used STPA to develop a framework to identify safety indicators for occupational accident mitigation in the fish farming industry. Thirteen indicators were identified, and, after evaluation, nine were left for possible implementation in the safety management of a fish farm company. The case study proves that the systems theoretic approach of STPA is well suited for analysis of safety control problems at fish farms. However, the framework is extensive and would require considerable resources for a complete analysis (Holen and Utne, 2018).

2.4.2 Analysis of events reported to the regulatory authority

Analyses of aggregated accident and incident data facilitate learning from multiple events (Kjellén and Albrechtsen, 2017). Norwegian fish farming companies are required to report accidents and incidents related to fish health, fish escape, emissions to the environment, food safety, and occupational safety to the regulatory authorities. The authorities use the aggregated data to monitor safety performance and identify needs for improved risk-reducing measures at an industry level. This can be, for example, new regulatory requirements, information campaigns, safety inspections, or safety audits.

The accident and incident databases should be interpreted with caution. Causal-sequence accident models have dominated the systems for standard accident reporting and which accident data to be collected, describing the accident as a chain of multiple events. There is no distinction between observable facts and the possible influence from human and organisational conditions (Kjellén and Albrechtsen, 2017).

2.4.3 Inspections according to regulatory requirements

Inspections may be conducted by regulatory authorities, third parties, or by company internal inspection teams and focus on the compliance of a specified system according to the requirements, e.g., work procedures, the state of a technical structure, or a vessel operation.

All main components of a fish farm shall be documented and identified in a user handbook. A "Construction certificate" is required to prove—or "measure"—the technical condition of the fish farm. The procedure is as follows: The fish farm is audited by a third party auditor who checks documents and performs a technical inspection of all main components, construction parts of the moorings, and extra equipment. The auditor may detect nonconformities which have to be closed before the certificate is issued. The Fdir receives a report when the certificate is obtained.

Regular inspection and maintenance of farm structures and components are required by NS 9415 according to the intervals advised by technology manufacturers (Standard Norway, 2009). These inspections are performed by fish farm personnel or specialised service vessel crews. Deviations regarding the condition, maintenance intervals, or use of equipment, components, and farm structures are associated with the safety of an operation involving that piece of technology and shall be registered as a nonconformity (see next subsection). Furthermore, the Fdir escape database contains information on escape events in which vessels, fish farm components, or equipment have been identified as contributing to a hazardous event. This knowledge is used by Fdir in their work as the regulatory authority, and learning points are fed back to the industry and may hence be used for improving safety management of the component or asset in question.

2.4.4 Reporting of nonconformities (company internal)

Fish farm companies are required to register hazardous events and nonconformities as part of their internal control system to evaluate compliance with regulations (Ministry of Labour and Social Affairs, 1996; Ministry of Trade and Fisheries, 2004). The nonconformities may be related to a technical failure or a work practice which deviates from the procedure as described in the company's quality management system. Registrations shall be followed up by identification of the causes for the deviation and subsequent implementation of corrective actions. The treatment of nonconformances is thus a tool to continuously improve safety performance by capturing and managing hazards related to the daily operations, fish treatments, work environment, and material assets. This may also provide input to the risk assessments.

2.4.5 Risk assessments

Risk assessment is a core activity of safety and risk management. Risk assessment is important as a tool to control and reduce risk levels to what is acceptable. Five risk dimensions in the Norwegian aquaculture industry were described in section 1.6. The seven areas derived from the aquaculture regulations (cf. Figure 4) are commonly documented by separate risk assessments. The regulatory requirements for what to include in risk assessments are presented in article 4 (Holmen et al., 2018).

The regulatory framework does not give instructions for the risk assessment process as such. The technical standard for marine fish farm constructions, NS 9415 (Standard Norway, 2021a), refers to the Norwegian standard on requirements for risk assessments, NS 5814, which was updated recently (Standard Norway, 2021b) . The previous version of NS 5814 (Standard Norway, 2008) was used in the study on risk assessments in the aquaculture industry (Holmen et al., 2018). The risk assessment process, as recommended by the updated NS 5814, is shown in Figure 7.

2.4.6 Safety indicators

A RIF may be considered a theoretical variable which is difficult to measure directly (Øien, 2001). *Indicators* are therefore used to measure its condition (Øien et al., 2011a). There are two main types of indicators used to describe a RIF, risk indicators for use in quantitative risk models (Øien, 2001; Haugen et al., 2011) and safety indicators (Øien et al., 2011b; Swuste et al., 2016). Several indicators may be needed to fully describe one single RIF.

According to Øien et al. (2011a), a risk indicator is identified from quantitative risk analyses and risk-based models. Safety indicators are identified based on accident models other than risk models—e.g., incident-based approaches—and are used as a measure of past, present, and future safety levels. In the context of this thesis, *safety indicator* will be applied.

Safety indicators are used both for measuring the state of risk control measures (leading) as well as for measuring the outcome or losses of an event (lagging). Kjellén (2009) explained leading safety performance indicators as variables able to detect evolving changes in risk levels. The UK Health and Safety Executive (HSE, 2006) defined leading and lagging relative to barriers in the Swiss cheese model (Reason, 1997). Each slice in the model represents a safety barrier function, and leading indicators are used to monitor the stability of the barrier during regular routine checks. On the other hand, lagging indicators are "holes" in the barrier detected after an incident. HSE (2006) defined lagging indicators generally as failures occurring during normal operation.

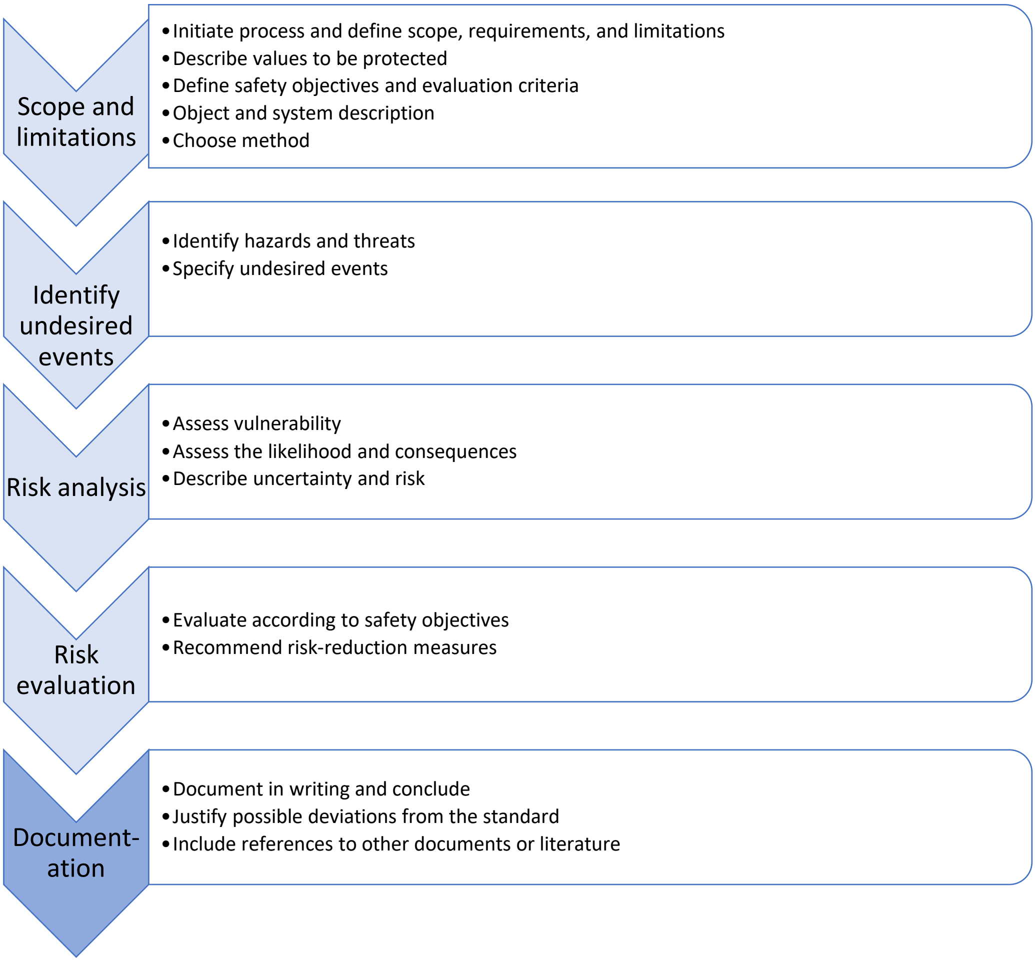


Figure 7 Main steps of the risk assessment process according to NS 5814 (Standard Norway, 2021b).[4]

Leading indicators may also be explained as parameters that predict the future safety performance of a company or give an early warning of a deteriorating risk control. Lagging indicators are commonly understood as measures of failures of the safety management system. Leading indicators are coupled to proactive measures and lagging to reactive monitoring (Øien et al., 2011a). The bowtie model (see de Ruijter and Guldenmund (2016) for a review) has been used to illustrate the difference between

[4] Figure 7 - Main steps of the risk assessment process according to NS 5814 is reproduced by I.M. Holmen in the doctoral thesis "Safety in Exposed Aquaculture Operations" under licence from Standard Online AS November 2021 (c). All rights are reserved. Standard Online makes no guarantees or warranties as to the correctness of the reproduction. In any case of dispute, the Norwegian original shall be taken as authoritative. See www.standard.no

leading and lagging indicators, which might be useful for practitioners. In this model, leading indicators are explained as the variables monitoring the state of the barriers and probability of rising risk levels on the left side of the undesired event, and the lagging indicators measure the state of the barriers and consequences on the right-hand side (Swuste et al., 2016).

Safety indicators may also be categorised differently. Kjellén and Albrechtsen (2017) linked three categories of safety indicators to their accident analysis framework shown in Figure 6: i) indicators related to factors influencing a deviation (early stage RIFs), ii) indicators associated with the stages from when the deviation occurs till the accident is inevitable, and iii) measurements of loss (e.g., number of injuries, size of leaks, technical failures). These categories could also be relevant for monitoring safety performance in the fish farming industry.

Bayesian networks (BN) are graphical models often used to illustrate the causalities between RIFs and an undesired event (Rausand, 2011). Influence diagrams and BN are terms used interchangeably in scientific literature, although BN might be explained as the network resulting from the development of the influence diagram (Hong and Apostolakis, 1993). Bayesian networks have been implemented in an increasing number of industrial, environmental, and financial applications and fields (Marcot and Penman, 2019). The application of BN as the basis for risk-influence modelling and identification of indicators has been demonstrated within the oil and gas sector (Øien, 2001; Vinnem et al., 2012; Pasman and Rogers, 2014) as well as in the maritime industry (Trucco et al., 2008; Hänninen et al., 2014). The strength of BNs also stems from the different types of risk-influencing factors that may be modelled in the same system, which means that the risk models may include organisational and human factors in addition to technical ones. Hence, BN, or graphical networks in general, are flexible tools for organising, visualising, and modelling the knowledge about hazards and RIFs in a defined system.

MARI is an abbreviation for Major Accident Risk Indicators and was developed by Haugen et al. (2011) for identification of major accident indicators for monitoring and predicting risk levels in the oil and gas industry. A step in the MARI method is to establish a qualitative RIF model, including all key factors which influence the major accident risk, including technical, organisational, and human ones, as well as the influence between the different risk factors (Haugen et al., 2011; Seljelid et al., 2012). The model is structured into three layers: preconditions, planning and coordination, and activity causing the (undesired) event. Barriers were also included as factors in the model. Nordtvedt (2016) has previously shown this method to be promising for developing a risk model for fish farming operations.

2.4.7 Safety performance audits

Assessments of the organisation's compliance with safety regulations and internal safety requirements are conducted by safety audits. Audits can be performed by external bodies, e.g., by a third party or regulatory authorities, or through internal audits performed by the organisation itself. ISO defines audits as *systematic, independent, and documented processes for obtaining audit evidence and evaluating it objectively to determine the extent to which audit criteria are fulfilled* (ISO, 2018a). Employees from another department than the one being audited should preferably be the ones who conduct internal audits. In Norway, internal control is a regulatory requirement for fish farmers, as well as other industry companies, to ensure quality in their safety management system (cf. section 2.2).

Organisational conditions influencing risk may be difficult to capture using indicators alone. The operational safety condition method (OSC) is a qualitative method aimed at closing this gap by auditing the risk-controlling systems related to a defined major accident (Kongsvik et al., 2010). Organisational RIFs are identified in documentation on accidents, incidents and deviations, staff interviews, and observations of safety management practices. OSC is described in more detail in section 2.4.7.2.

Safety climate questionnaires have also been used as a supplement to quantitative indicators to measure workers' attitudes to and perceptions of safety at the workplace (Kjellén and Albrechtsen, 2017). Sets of questions and their scores make up the indicators. Five organisational topics are usually included: management, aspects related to the safety management system, perceptions of occupational risk, work load, and competence (Flin et al., 2000). Section 2.4.8.2 presents results from a safety climate study in the Norwegian fish farming industry.

2.4.7.1 Technical Safety Condition (TTS)

As aquaculture production technology advances, with increased levels of autonomy and remote operation, there will be a need for tools to monitor the technical performance and state of safety barrier functions. It is relevant to look to well-established ocean industries for effective methods for adoption. In Norway, the offshore oil and gas sector has been in the lead regarding both technological innovations and systems to manage major accident hazard risks. A couple of decades ago, a Norwegian oil and gas company implemented TTS as a tool to review technical safety systems and safety barriers for offshore production systems (Ingvarson and Strom, 2009).

TTS was initially developed as a tool to monitor and ensure a high safety level on the offshore production units (Thomassen and Sørum, 2002). Management Regulations require the Norwegian oil and gas industry to establish barriers and monitor their performance (PSA Norway, 2019a).

There are four main objectives of TTS: 1) to assess the function of safety barriers, 2) to increase the awareness and competence of operational safety among operators, 3) to act as a tool for major risk management, and 4) to document compliance with regulations. The basis for TTS is the barrier functions identified in the chain of events that might result in a major accident. Thereafter, twenty-two generic performance standards (PS) related to each technical safety (barrier) function were defined. The set of PSs is established as a generic list for the facilities in the oil and gas industry. Three examples are "containment function," "gas detection," and "well barriers." Detailed performance requirements (PR) are identified for each PS, covering the essential functions of the barrier systems, the integrity, the survivability in case of a major accident, and competence and procedures needed for barrier management. Several aspects of the performance of each barrier function are examined by checkpoints defined for each PR. The checkpoints need to be revised according to the current company requirements or industry standards. Each checkpoint is individually evaluated in terms of design (internal, external, best industry practice), physical/technical condition, and operation (knowledge, training, procedures). Altogether, the checkpoints and their evaluation properties make up a detailed checklist which is used by the verification team to conduct the assessment itself. This is conducted as an audit combining interviews, document reviews, visual inspections, and testing.

The properties of each checkpoint (i.e., design, physical/technical condition, operation) are given a score from zero to three according to their conditions: unacceptable (0), nonconformity/poorer than norm (1), conforms to today's requirements/good practice (2), better than norm (3). A grading system sums these scores up into a grade (a to f) for each checkpoint. The grades for the checkpoints are further aggregated into the level of each PR, which are rated according to grades (A to F) (Ingvarson and Strom, 2009). "A/a" is the best grade ("significantly better than the performance requirement"), "B/b" is given when the condition is in accordance with the reference level, "C/c" is satisfactory, and "D/d" is within the minimum safety level of the statutory regulations, hence good enough to pass but deviates significantly from the reference level. Grade "E/e" describes a condition with significant deficiencies, and "F/f" is not acceptable. The results of the TTS audit are thus a list of performance standards (PS) with a number of correlated PRs rated A–F to express whether they comply with the requirements or not. Corrective actions are identified and prioritised in a workshop with site personnel. Internal requirements set the assessment cycle to five years for all sites (Ingvarson and Strom, 2009).

2.4.7.2 Operational Safety Condition (OSC)

The OSC method was selected for possible adaptation to the aquaculture industry (objective 3). OSC was originally suggested as a supplement to assessments of the state of technical components and systems in a production facility, i.e., to the TTS method (Kongsvik et al., 2010). OSC was developed based on the same basic principles as TTS and aims to identify organisational risk factors linked to a certain undesired event (leakage of hydrocarbons, i.e., oil spills). The objective was initially to assess the operational safety condition on a petroleum installation, with a special focus on mitigating major accident risks and the effect of human and organisational factors on the performance of operational barriers (Vinnem et al., 2007). In the original work to develop OSC, a literature study of organisational risk-influencing factors was performed, and fifty-five relevant factors were found (Kongsvik et al., 2010). Further work to prioritise and merge factors resulted in a list of seven factors: work practice, competence, procedures and documentation, communication, workload and physical environment, management, and change management.

The steps of the OSC method are similar to TTS (Kongsvik et al., 2010). The first step is to identify the causes for the undesired incident/major hazards to be analysed. The chain of events may be found in accident reports, as well as investigations reports. In-depth interviews with operators and workshops are used as a source of qualitative information. Step two is to map the work operations with high risk for fish escape. These may be found in the same sources used in step one. Step three is to develop a list of organisational factors with significant influence on the performance of the operations. Applying this method in the oil and gas industry identified seven organisational risk factors (see previous paragraph). The fourth step is to establish a list of internal and external requirements connected to each factor, resulting in a description of safety performance requirements. Sources for these requirements are typically legal regulations and company internal practices. Other written sources may be international standards with which the company wants to comply. Once the requirements are gathered, checkpoints are formulated based on the requirements (step five). These form a checklist used in the assessment, which is step six, for conducting the audit with employees representing all levels in the organisation from top managers to operators. The OSC audit is documented with a summary of the checkpoints and evaluations of compliance with external and internal requirements. Every requirement is graded A–F as in the TTS method. Finally, the report is presented to management. Follow-ups are recommended to develop measures for the potential hazardous conditions revealed by the OSC audit, e.g., a workshop for the workers at the installations (Kongsvik et al., 2018a).

OSC can be used as a supplement to the internal audits as required by the Internal Control regulations in the aquaculture industry (Ministry of Labour and Social Affairs, 1996; Ministry of Trade and Fisheries, 2004). The OSC revision may detect deviations from formal requirements and internal work procedures and hence be a useful tool for evaluating safety measures and improving safety management at fish farms.

2.4.8 Current safety management performance

This section presents recent safety management performance measurements concerning risk of fish escape and occupational risk in the Norwegian fish farming industry at authority, company, and fish farm levels.

2.4.8.1 Fish escape

Measures to prevent fish escape are highly prioritised due to the potential harmful consequences for wild salmon stocks and economic losses. Fdir is the regulatory authority for aquaculture licences, fish farm structures, and prevention of fish escape. All fish escapes must be reported to Fdir, with specifications covering the number of lost fish, type of fish farm, and direct and contributing causes (Directorate of Fisheries, 2021b). Fdir uses this information to improve the regulatory requirements and to highlight hazards the fish farmers should take precautions against. The levels of fish escape have decreased due to systematic preventive efforts. The introduction of the technical standard NS 9415 improved the state of the primary barriers, the net cages, and mooring structures, and this resulted in a decline in escaped fish (Jensen et al., 2010). Implementation of the internal control regulations and aquaculture regulation seems to have had a positive effect after 2010. However, since 2013, the number of escaped salmon relative to the number of farmed salmon seems to have levelled out. Føre and Thorvaldsen (2021) drew attention to human and organisational factors which should be analysed in addition to the technical causes.

Fdir conducted an audit for wellboats in 2018 to evaluate the safety management performance of wellboat operations at fish farms (Directorate of Fisheries, 2018a). The highest number of nonconformities was found regarding i) identification of hazards associated with escape and risk assessments, ii) procedures, and iii) preventive measures. Requirements on internal control according to the aquaculture legislation were not fulfilled. Furthermore, a potential for improvement was noted regarding emergency planning in case of accidents.

2.4.8.2 Occupational health and safety

The fish farm and aquaculture vessels are workplaces characterised by close contact between the operator and the occupational hazards. The risk of fish escape has been reported to be prioritised over the fish farmers' own safety (Størkersen, 2012). Serious occupational accidents at fish farms shall be reported to the Norwegian Labour Inspectorate Agency (NLIA). Occupational accidents and incidents at the vessel larger than fifteen metres shall be reported to the Norwegian Maritime Authority (NMA).

In the period from 2011 to 2019, the occupational injury rate based on registrations by NLIA have been between fifty to sixty injuries per 10,000 person-years, with an increasing trend from fifty-five in 2017 to seventy-three in 2019 (SINTEF Ocean, 2020). This may be explained by an increasing activity of complex operations like fish treatments. Holen et al. (2018a) analysed occupational injury data and found that the most frequent modes of serious injuries were blows from an object, entanglement/crush, or falls occurring during lifting operations or other operations involving ropes under tension or falls from ladders/height. An increase in injury rate was seen during the autumn and winter months, and this was associated with seasonal weather conditions.

There has on average been one fatality per year during from 2012 to 2020 (SINTEF Ocean, 2020). Analyses of fatalities in the period from 1982 to 2015 showed that loss of vessel was the prevailing hazardous event in the first and second decade, while failures during lifting and maintenance operations have been the main cause for fatal accidents after 2000 (Holen et al., 2018b). The occupational accident frequency and seriousness of the consequences is a concern to the NLIA (Norwegian Labour and Inspection Agency, 2021). NLIA prioritises inspections and information campaigns regarding equipment and work vessels, exposures to chemicals, working alone, and musculoskeletal problems. Fish farm workers are exposed to intermittent high workloads (Sandsund et al., 2022). Work-related strain injuries may be a cause for acute sick leave as well as chronic pains during the long term, which might force experienced workers to resign from working in fish farming (Thorvaldsen et al., 2020).

The recent project "Safer operations and workplaces in fish farming"[5] aimed to systematically investigate the occupational safety and health conditions in the fish farming industry. The project has resulted in increased knowledge about the status, items for improvement, and challenges related to safety management in the industry (Thorvaldsen et al., 2021). A survey was conducted to collect data on the workers' perceptions of their work environment and exposures, health complaints and status, sickness leave, occupational safety, job satisfaction, and safety climate. Employees at fish farms, work vessels, and service vessels were included (Thorvaldsen et al., 2017). The overall job satisfaction was good, and as much as 97% of the respondents are content at work. 85% of the workers regard themselves to be of good or very good health (Thorvaldsen et al., 2020). Physical exposures and unfavourable ergonomic work postures were commonly reported, and more than 50% of the respondents were worried about health hazards in the work environment. Conflicting objectives regarding prioritisation of work tasks are likely to influence work pressure negatively. The HSE survey should be repeated regularly to update the knowledge basis for development of preventive measures at company and fish farm levels.

Analyses of the safety climate were conducted to measure safety management performance at company and fish farm management levels (Kongsvik et al., 2018b). The focus of this survey was OHS practices, but the results may also be valid for operational safety in a holistic perspective. One of the questions asked was "Were risk assessments performed during the last four years at the fish farm?" More than 98% answered, "Yes." Furthermore, 90% of the respondents confirmed that safe-job analyses are used before complex, infrequently conducted work operations. The survey also contained questions relevant for safety management, e.g., compliance with safety rules and procedures, management of safety, reporting of events and nonconformities, internal control, audits, and inspections. All in all, 60% of the respondents rated the systematic safety work in their company to be very good and noted that the safety levels within the company had increased during the last two years. However, the results showed that the safety management systems may be better integrated in daily work, and the internal procedures are regarded as too complicated for practical use. Reporting of hazardous events is a prerequisite for development of preventive measures and for experience feedback in the control loop (Figure 5) (Kongsvik et al., 2019b). The various aspects associated with the

[5] Researcher project financed by the Research Council of Norway and managed by SINTEF Ocean (2016-2019) [grant no. 254899].

analyses of safety climate in the fish farming industry provide learning points which are useful input to continuous improvement of safety management at the fish farms.

Further analyses of the HSE survey data found a correlation between safety climate and self-reported health complaints (Kongsvik et al., 2019a). Involvement in safety decisions (i.e., decisions on purchase of new equipment and development and implementation of new work procedures) and work pressure (in particular, perceptions of safety being sacrificed to efficiency and production) were the two factors showing a significant negative correlation with headache, fatigue, and musculoskeletal pain in upper limbs and the neck. The results implicate that human health hazards need to be better managed at fish farms and that workers need to be adequately involved in safety decisions.

2.5 SAFETY MANAGEMENT OF FUTURE EXPOSED AQUACULTURE

Authorities have directed attention to several challenges associated with future seafood production utilising sea areas which currently are too exposed for today's fish farm technology. The report "Offshore Aquaculture" addresses technical standards and operations of farms, personnel safety, environmental risks, and fish welfare and health in light of the current regulatory regime (Ministry of Trade and Fisheries, 2018a). Recommendations from the report are included in this section.

The technical regulations for the installations and the requirements for escape prevention need to be evaluated according to the rougher operating environment. The technology solutions and equipment must be designed to function in these conditions and require easy maintenance to make up for reduced availability. Sensor systems may assist daily inspection may by enabling remote observation of fish and barrier functions. The implementation of autonomic concepts with varying levels of autonomy could potentially reduce risks (Utne et al., 2015). A recent study has provided important contributions to the technology development needed to increase the level of autonomy in operations for inspection, maintenance, and repair of fish cages (Holmen et al., 2019; Sandøy et al., 2020). Furthermore, an indicator program similar to the Risk Level project (RNNP) in the Norwegian oil and gas industry should be considered for implementation in the fish farm industry (Utne et al., 2017). RNNP consists of a set of technical safety indicators which monitor the function of safety barriers to mitigate major accident risk (Vinnem, 2010; PSA Norway, 2019c).

Discussions have arisen over whether the Working Environment Act is applicable or if the maritime Ship Safety Act (Ministry of Trade and Fisheries, 2007) and Ship Working Act (Ministry of Trade and Fisheries, 2013) are a better match for offshore aquaculture workplaces, since the risk picture resembles maritime and petroleum offshore industries. Increased distance to shore may increase emergency response times in case of material damage, fish escape, or occupational accidents, and the dimensioning of the resources for mitigating possible accidents must reflect this. Adequate competence and staffing are also listed as important requirements due to their impact on safety performance.

One of the main arguments for investigating the possibilities of exposed aquaculture is to reduce environmental impact. Still, many of the same challenges found in coastal fish farming will be present, e.g., waste disposal, emissions of possible toxic agents and pollution, and threats to wild salmon due to escapes or parasites. To support environmental risk management and reduce negative impacts, reliable systems for monitoring the emissions and total exposure are needed.

The current Food Act (Ministry of Health and Care Services, 2003), Animal Welfare Act (Ministry of Agriculture and Food, 2009), and other legislative requirements for ensuring good fish welfare and health are regarded as sufficient also for offshore aquaculture. However, studies indicate that salmon and in particular cleaner fish may not thrive in high current flows and rough seas (Hvas et al., 2019). To ensure responsible fish farming, future sites need to be properly evaluated regarding fish welfare. Regular monitoring of indicators which reflect changes in fish welfare is needed to ensure the safety and proper treatment of the fish.

3 Research Methodology

The first part of this chapter is a reflection upon the research and research impact and the research methodology in general and in the context of safety science. The second part of the chapter presents the research approach in the PhD project, quality assurance and ethical issues.

3.1 Methodology

3.1.1 Research definition and classification

According to the Oxford English Dictionary, *research* is a "systematic investigation or inquiry aimed at contributing to knowledge of a theory, topic, etc., by careful consideration, observation, or study of a subject" (Oxford ED, 2021). The same dictionary defines *development* as "the action or process of bringing something to a fuller or more advanced condition, spec. the explanation or elaboration of an idea, theory, etc."

OECD registers research activities to monitor the trends of research efforts in OECD countries. To produce internationally comparable statistics for financial and human capital invested in R&D, a manual has been developed to describe a common standard for gathering, analysing, and reporting key figures (OECD, 2015). Their definition of R&D is as follows:

> Research and experimental development (R&D) comprise creative and systematic work undertaken in order to increase the stock of knowledge—including knowledge of humankind, culture and society—and to devise new applications of available knowledge (OECD, 2015).

Furthermore, three types of R&D are considered (quotations from OECD (2015)):

1. *Basic research*: experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.
2. *Applied research:* original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific, practical aim or objective.
3. *Experimental development:* systematic work, drawing on knowledge gained from research and practical experience and producing additional knowledge, which is directed to producing new products or processes or to improving existing products or processes.

The research in this thesis falls within the category of applied research, according to the objective of developing knowledge and methods for improved management of operational safety in exposed sea-based fish farming. Furthermore, the results are the basis for experimental development conducted by the industrial partners in SFI Exposed.

3.1.2 Research designs

In a review of more than 1,900 research papers, Chu and Ke (2017) systematically extracted information about research methods. Research methods consist of two main categories: data collection and data analysis. Research methods should be classified according to the data collection technique, e.g., qualitative data require qualitative methods and are categorised as qualitative research, specified by the type of data collection (e.g., interviews) (Chu and Ke, 2017). The target group of this study is librarians rather than researchers; however, it brings attention to the importance of being consistent regarding data collection methods and appropriate techniques for analysing the data and describing this clearly in articles to facilitate easy access by research fellows in the scientific community.

There are qualitative and quantitative research methods, and a mix of these may be applied according to the research questions to be addressed or hypothesis to be tested (Creswell, 2017). The research should be reliable, valid, and possible to generalise. These three criteria for research quality are universal (Tjora, 2021).

Pure quantitative research collects numbers or values of parameters, which may be measures using loggers and instruments. The analyses are numerical, and statistical methods can be used to test the hypothesis in question.

Qualitative research is about learning from realities in society (Leavy, 2014). Qualitative research methods are characterised by being close to and interacting with the organisation or the human population to be studied. The approach is driven by gathering empirical data to explore (Tjora, 2021). Case studies are a common approach to limit the amount of collected empirical data. Case studies are a recommended strategy in projects aiming to gather knowledge about the case itself, rather than about the informants as such. Data collection techniques relevant for case studies may be qualitative (e.g., interviews, observations, focus groups, documents, and literature studies) or quantitative methods (e.g., analyses of data registries or extracting quantitative data from existing processes) or a combination (e.g., surveys). Interviews may be structured, unstructured, or semi-structured (Leavy, 2014). Structured interviews strictly follow an interview guide or a fixed set of questions and may be conducted as web-based surveys. Unstructured interviews entail giving the informant a cue about the topic in the beginning, and the interviewer mainly listens and only interrupts to clarify the story. Semi-structured interviews follow a list of topics the interviewer wants to cover during the interview to collect data on subjects relevant for the research project.

Qualitative research may also be quantified. An example is questionnaires used in safety climate studies. The respondents are asked to grade their response to a question or a statement according to a scale, e.g., integers from one to five where one represents strongly disagree, five strongly agree, and three neutral. By applying statistical techniques to the ratings, indexes can be calculated which are correlated with the safety-related conditions formulated as statements in the questionnaire (Guldenmund, 2000).

Interdisciplinary research combines two or more disciplines with regard to perspectives, technology areas, and research methods, which are necessary conditions to solve certain problems (Pruzan, 2016). SFI Exposed is an example of an interdisciplinary research centre (Bjelland et al., 2015). The research areas are autonomous systems, decision support, structural design, vessel design, fish welfare, and safety. To work with the problems addressed, the centre employs researchers from social sciences, marine biology and ecology, as well as a range of engineering disciplines.

3.1.3 Safety research progress and challenges

The safety concept has emerged from the consumption of human labour during the growth of the industrial age to a practice of managing occupational safety in national regulations and making company management responsible for safety performance within organisations (Swuste et al., 2020). Safety management systems are now mandatory in several industries at the company level and have been the focus of safety science since 1973 (Li and Guldenmund, 2018).

Safety science is by nature interdisciplinary and has implemented concepts and theories from, for instance, the social sciences (culture, organisation, and system theories) and mathematics (risk) (Swuste et al., 2020). Studies within maritime and marine safety also apply a variety of qualitative and quantitative research methods and multidisciplinary approaches (Bye et al., 2021). Additional applications and fields for safety research continue to emerge, e.g., from new technologies or effects of climate changes. These are currently handled as separate issues by experts within different academic disciplines due to the complexity of the systems addressed. This multi-disciplinarity may be a challenge for the further development of safety science as a unified research domain (Swuste et al., 2020).

The development of multiple safety subdomains has resulted in an increasing number of specialised safety researchers and scientific publications (Goerlandt et al., 2021). However, the empirical contributions to the scientific literature are few compared to the number of theoretical articles (the ratio being approximately one to five) (Rae et al., 2020). The flow of scientific articles may thus not contribute to further progress of safety in practice because they are not evaluated by practitioners or demonstrated to improve safety management systems.

There thus seems to be an increasing gap between safety as a science and safety in practice. Authorities may adopt the state-of-the-art safety theories to improve regulatory requirements despite these not having been evaluated in practice (Rae et al., 2020). Safety regulations may also be copied to new industries without considering that different external or internal conditions may not align with the requirements (cf. section

2.2). The result is safety management decrees that do not support safe practices within their respective workplaces.

The trend of shifting from detailed, specific safety rules to so-called functional regulatory requirements has increased the number of company-internal safety procedures and subsequently requires more resources for internal control activities (Størkersen et al., 2020). A recent study demonstrates this point in the fishing and maritime industries. Fishers and seafarers find the regulatory requirements for safety management too resource demanding to implement and not useful in practice (Størkersen and Thorvaldsen, 2021). Swuste et al. (2020) suggested that both these abovementioned challenges can be solved by encouraging scientists and industry practitioners to jointly develop tools for safety management and evaluate them in a real-world setting.

Due to the increasing complexity of the risk picture in high-tech industries, there is a need for a shift from merely designing risk-reducing measures complying with regulations to also being prepared for unanticipated events (Swuste et al., 2020). Identification of new hazards and emergency preparedness for the "unknown" thus should be given greater attention in future safety management systems.

3.2 Research approach in PhD project

3.2.1 Research project plan

The safety research area in SFI Exposed is anchored to the aquaculture industry's needs related to operational risk management and safe fish farming at more exposed locations. This has shaped the PhD project in that the results should be applicable and highly relevant for the industry in the short term but also contribute to improved safety and risk management in the longer term. The research activities were hence designed to ensure true involvement of operators, safety personnel, and middle and top management, as well as the regulatory authorities, to capture the basic needs and flaws in the current safety management of fish farming. Accordingly, a project plan was developed during the first semester of the PhD study at the Department of Marine Technology, NTNU. The milestones and topics of the work packages have been adjusted during the study according to its progress and the results from parallel R&D activities.

Figure 8 shows that the PhD project has been a part of a systematic effort to increase knowledge about and improve safety levels in fish farming operations.

Chronologically, the study described in article 2 (Thorvaldsen et al., 2015) was the first to be conducted. It played a major role together with the safety research in the research project Sustainfarmex[6] to document the need for a long-term research effort on safety

[6] Sustainfarmex (2012–2015) was a knowledge-building research project funded by the Research Council of Norway [grant no. 210794].

and risk management in the aquaculture industry (Holen, 2019). This was continued within SFI Exposed. It also sparked the idea of studying causal mechanisms and risk-influencing factors in fish farming applied to fish escape throughout the PhD work presented in this thesis.

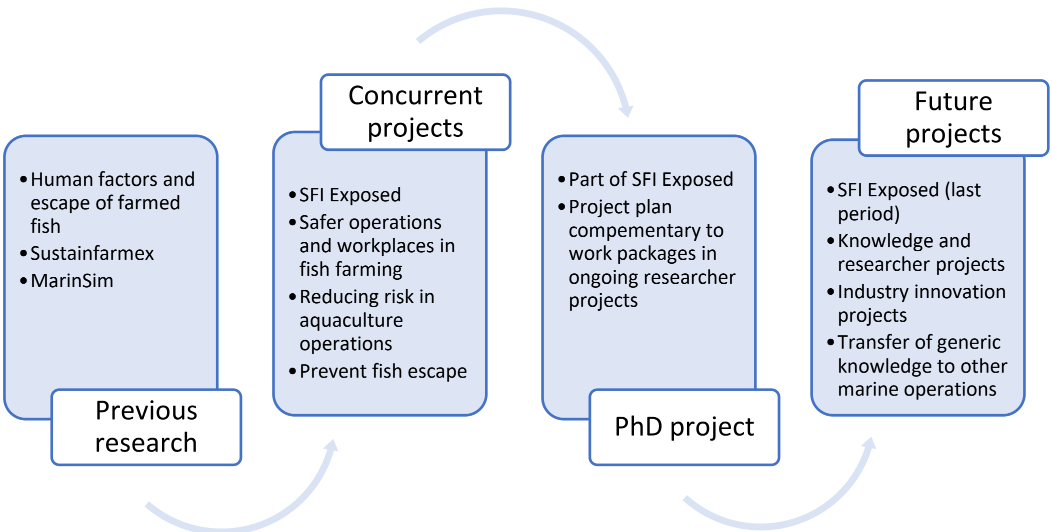


Figure 8 The PhD project in the context of systematic research efforts[7] to increase knowledge about operational safety conditions and develop measures for reducing risk and accident prevention in the fish farming industry.

3.2.2 Research methods applied

This section is a general discussion of the choice of research methods in the PhD project. An overview of the data material and methods applied in the articles is included in Chapter 4 as a basis for the contributions to each objective.

The PhD project mainly consists of qualitative research and is a case study of fish escape from Norwegian fish farms. The methods chosen for data collection were a combination of semi-structured interviews, workshops with experts, field observations, and review of safety documentation shared with us by the companies. These methods are well-proven in previous safety research projects within fishing, processing of fish, and fish farming, which all are workplaces characterised by a high degree of manual tasks and the presence of high energies in the work environment. The research is interdisciplinary, combining knowledge from multiple research disciplines and fields relevant for fish farming, e.g., biology, veterinary medicine, social sciences, engineering, and safety science.

[7] See List of Publications for more information on the projects in Figure 8.

Fdir authorised access to the fish escape event database, which was the basis for analyses and categorisation of causes and contributing factors. It is mandatory to report fish escape events, both confirmed accidents and suspected escape (Ministry of Trade and Fisheries, 2018b; Directorate of Fisheries, 2021b). The Fdir database is unique in that it is a national registry of fish escape accidents *and* no escape incidents, i.e., near-misses. Previous analyses of the Fdir database are based on confirmed escapes only, excluding the no-escape events. However, near-miss reporting is important and may support identification of causal chains and preventive measures otherwise not revealed (Jones et al., 1999; Kjellén and Albrechtsen, 2017).

Initial quantitative analyses (frequency counts) were applied on the fish escape report data. To further analyse the data, expert judgement and graphical networks were applied to identify chains of events. Previous analyses of contributing causes to fish escape events and expert judgement were applied to re-categorise the Fdir database. In one of the articles, a qualitative BN model was applied to keep track of all conditions and factors extracted from the escape data and other available analyses as a basis for identifying relevant RIFs.

3.3 Quality assurance

The four journal articles in the thesis have been quality assured during peer review in international journals. The articles were submitted to different journals in order to present the application of safety research methods in fish farming to different professional and academic research communities. The conference article was presented at an international conference after undergoing review for acceptance. Drafting the manuscripts involved a long process of planning studies, collecting and analysing data, and writing manuscripts, during which the supervisors and colleagues (first authors/co-authors) and the PhD candidate have been a team. Findings from the research have also been presented at Exposed partner meetings and workshops, international conferences, and national seminars. These activities have provided valuable feedback about the state-of-the-art safety performance and challenges in the fish farming industry and the relevance and practical use of the results and have also laid a solid foundation for current and future research projects in collaboration with industry actors.

3.4 Ethical issues

The project has been evaluated according to the research ethical checklist issued by the national committees for research ethics in Norway. Human subjects have been involved through personal interviews, workshops, observations, and measurements at workplaces. The data collected using such methods has been essential to achieve the objectives of the project. To ensure privacy protection of the subjects, the research has been carried out according to the Personal Data Act in Norway and accordingly reported to the Data Protection Services unit operated by the Norwegian Centre for Research Data (NSD).

When required, written informed consent has been obtained from the participants. They were informed that their personal answers would not be forwarded to their employers or any other persons beside the project co-workers. On a longer term, the results from this project will contribute to improved working conditions and reduced occupational risk for workers in the aquaculture industry. Furthermore, the results will also contribute to reduced risk of fish escape and risk to fish welfare and the external environment, which is positive for the reputation of the industry and hence also may improve the psychosocial working environment for the participants in the research.

4 MAIN RESULTS AND DISCUSSION

This chapter summarises the main results and findings in the studies performed as a part of the PhD project according to the research objectives. Figure 9 gives an overview of the main objective, research objectives, and scientific articles. Each article contributes to one or more of the objectives. The contributions from the articles to each objective are presented in sections 4.1–4.5. The impact of the research contributions is discussed in terms of theoretical contributions and practical applications in section 4.6.

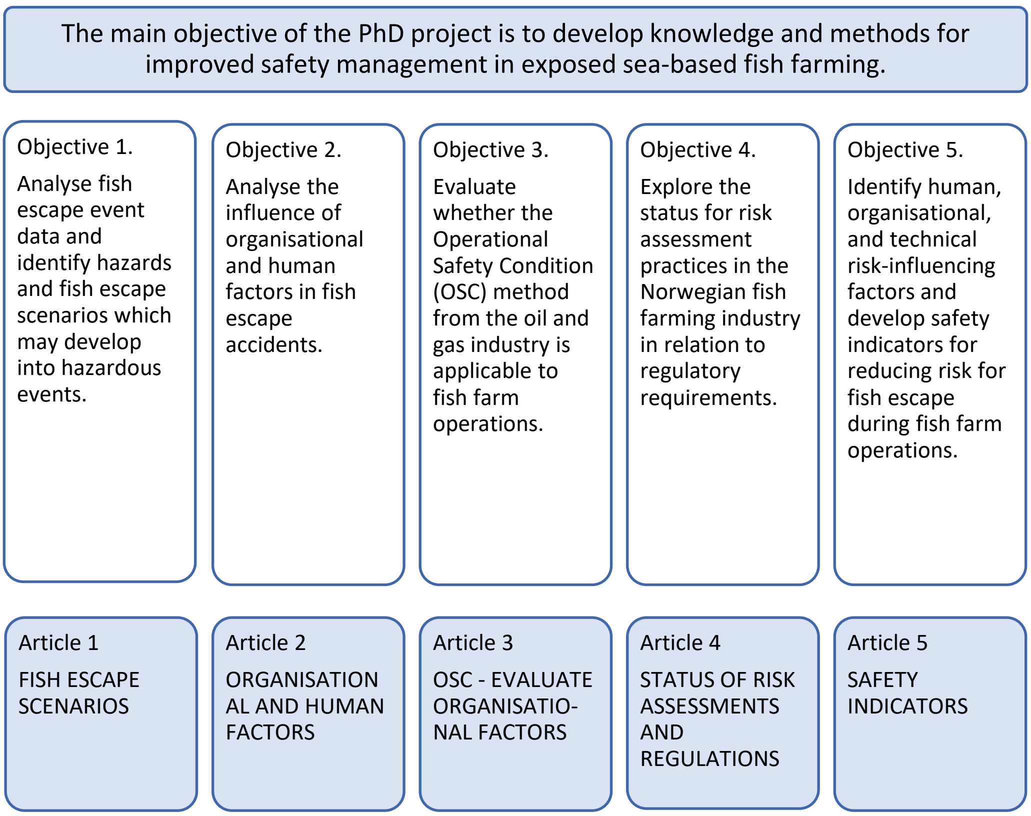


Figure 9 Overview of the objectives of the PhD project, and the scientific articles which target one or several of the objectives.

4.1 Objective 1: Identification of hazards and fish escape scenarios

The first objective (O1) was to analyse fish escape event data and identify the hazards and fish escape scenarios which may cause hazardous events and result in accidents. Knowledge about the chain of events may be used to improve risk management and fish escape prevention strategies, as well as act as a basis for emergency planning.

Two of the articles contribute to this objective (Figure 10). Article 1 is the main deliverable on the fish escape scenarios (Yang et al., Under review), while the results from research article 5 (Holmen et al., 2021) add knowledge regarding the range of hazards and causal chains with interlinked contributing factors and conditions.

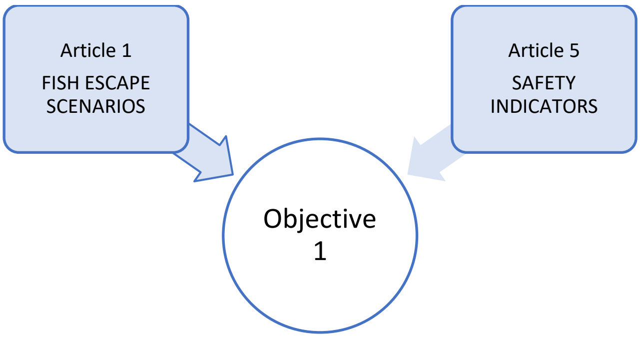


Figure 10 Articles 1 and 5 contribute to objective 1.

4.1.1 O1: Data material and analyses

The basis for the analyses in articles 1 and 5 is the fish escape database maintained by the Directorate of Fisheries (Fdir). The database is a collection of historical registrations of fish escape event data reported by fish farmers as required by regulations. The aim of article 1 is to identify and discuss a representative set of fish escape scenarios. 745 registrations of salmon and trout escape events between January 2006 and August 2019 are included in the analyses for article 1, including both accidents (confirmed escapes) and incidents (near-misses, i.e., no escape was concluded). Sixty per cent are no-escape events.

In the original dataset from Fdir, the registrations of fish escapes are sorted according to the size of the escape and five coarse event categories, namely external event, operational failure, structural failure, unsolved case, and not relevant. Causes are not registered in a systematic manner. Initial analyses concluded that this database design did not capture the most frequent escape scenarios and the complex causal chains. Hence, a re-categorisation of the database is conducted, as described in article 1. Due to missing data, 502 of the registrations in the Fdir database have been reanalysed into the new categories, 261 (52%) of which are no-escape events.

The study in article 5 aims to develop a methodology for identifying safety indicators in fish farming operations based on analyses of fish escape accident report data. One step of the method is to describe the causal chains illustrated in a Bayesian network (BN) (see section 4.5). The insight in the logical sequence of the chains of events is employed during the scenario building in article 1.

When needed for clarification of the escape event report details, technical documentation has been sought regarding the fish farm structures on the different manufacturer's internet homepages and in the technical standard NS 9415 (Standard Norway, 2009).

The registrations of fish escape events in the Fdir database are based on the mandatory reporting from fish farmers (Directorate of Fisheries, 2021b). The associated analyses are thus limited to the information reported by fish farmers, which is transferred and adapted to the categories in the Fdir database. The results may subsequently be influenced by subjective interpretation. Some events, in particular the no-escape events, are poorly described regarding causalities. The reason for this is that some hazardous events are discovered after time has passed, and information on contributing causes may be difficult to retrieve. For some of the events, expert judgements are used to fill in the blanks, applying knowledge gained during previous analyses of escape causalities and interviews with fish farmers. Furthermore, some events may likely went unreported, as underreporting generally is a challenge for accident reporting to the authorities (Kjellén and Albrechtsen, 2017). However, the Fdir database is built from fish escape event data gathered during several years and is regarded as representative of the different types of hazardous events which are likely to occur.

4.1.2 O1: Results

The contributions from the articles are three-fold. First, a range of hazardous events are identified based on a reanalysis of the Fdir database. Second, underlying factors and direct causes, which may influence the development and consequences of the hazardous events, are extracted from the available information in the database and previous analyses and systematised. The kind of operation going on (if any) is also identified. Third, causal chains are illustrated graphically as fish escape scenarios based on the re-categorisation of the fish escape data.

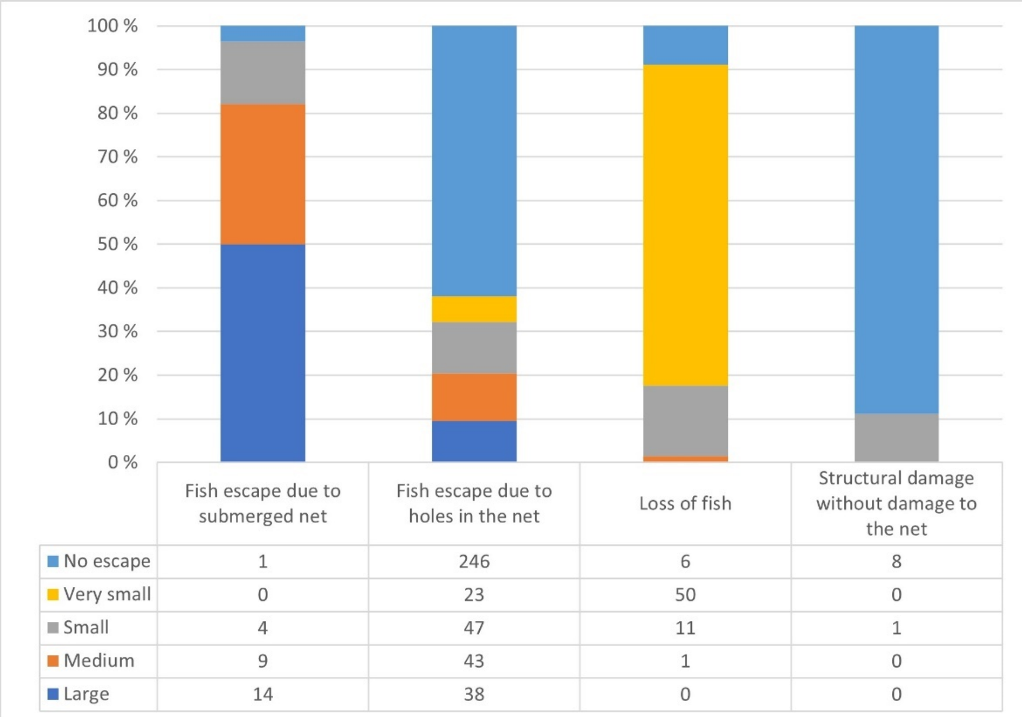
4.1.2.1 Hazardous events

Four main types of hazardous events are identified after the reanalysis of the fish escape database and described in article 1: fish escape due to 1) submerged net, 2) holes in the net, 3) loss of fish, and 4) structural damage without damage to the net. Type 1 and 2 are further broken down into subgroups (Table 3).

Table 3 The four main types of hazardous events and subgroups resulting from the reanalysis of the Fdir database presented in Yang et al. (Under review).

Type of hazardous event
1. Fish escape due to submerged net
a) Submerged net due to structural failures
b) Submerged net due to operational failures
c) Submerged net due to external events
2. Fish escape due to holes in the net
a) Net chafing causes holes (no operation ongoing)
a.i) Wear and tear from structures causes holes
a.ii) Wear and tear from mounted equipment causes holes
a.iii) Wear and tear without specified causes
b) Holes in the net due to net failures
c) Holes in the net due to operational failures
c.i) Holes in the net during mort collection operations
c.ii) Holes in the net during net cleaning operations
c.iii) Holes in the net during handling of stretching system
c.iv) Holes in the net while handling floating lines
c.v) Holes in the net caused by vessel contact
c.vi) Holes in the net due to damage from other extra equipment
d) Holes in the net due to lost items in the cage
e) Holes in the net due to external events
f) Holes in the net without specified causes
3. Fish escape due to loss of fish
4. Fish escape due to structural damage without damage to the net

Figure 11 presents the frequencies of the main types of hazardous events and the analysis in terms of consequence category (large, medium, small, very small, no escape). The hazardous event "holes in the net" is the major cause for escapes and near-misses and counts for 79.1% (397) of the 502 reanalysed fish escape hazardous events. 246 out of the 397 "holes in the net" events are near-misses; however, thirty-eight are large-scale events, hence the type of event which cause most serious accidents. Six subgroups of "holes in the net" events have been identified, two of which are further broken down into subcategories which identify the structures or operations that frequently result in a hole in the net. The full list of hazardous events associated with "holes in the net" are included in Table 3.



	Fish escape due to submerged net	Fish escape due to holes in the net	Loss of fish	Structural damage without damage to the net
No escape	1	246	6	8
Very small	0	23	50	0
Small	4	47	11	1
Medium	9	43	1	0
Large	14	38	0	0

Figure 11 The four main fish escape hazardous events after reanalysis of the Fdir database. The fish escape consequence categories (large, medium, small, very small, no escape) are presented as a percentage of the total number of events of each type. The figure is reproduced from Yang et al. (Under review).

The second-most-frequent hazardous event leading to severe consequences is "submerged net." Fourteen out of twenty-eight registered events are large-scale events, i.e., more than 10,000 escaped fish per accident, although this type of event accounts for only 5.6% of the re-analysed events. The three subgroups of "submerged net" specify the hazards resulting in a submerged net: structural failures, operational failures, and external events (cf. Table 3).

"Loss of fish" is the second-most-frequent in number (13.5%) in Figure 11, but four out of every five escape events in this category have resulted in a hundred escaped fish or fewer, i.e., they are very small-scale or no-escape events.

The fourth type of hazardous event, "structural damage without damage to the net," includes nine events, of which one resulted in a small-scale escape. The other eight were near-miss incidents. This category was included because these events have the potential for more severe consequences if the environmental forces were stronger.

4.1.2.2 Contributing causes and conditions

The analysis of the Fdir database identified a range of direct causes and underlying and coupling factors influencing the development of a hazardous event. These are presented in Table 4 and are the basis for developing the fish escape scenarios presented in article 1. The fish farming operations associated with the hazardous events are also included in the table. When needed for clarification, available information has been added from the analyses for article 5. The factors' interaction with the hazardous events in causal chains are illustrated as scenarios (see section 4.1.2.3).

Table 4 Direct causes, underlying and coupling factors, and operation ongoing (if any) identified from the original Fdir database. The causes and factors are sorted according to the four main hazardous events and may hence be repeated.

Direct cause	Underlying factors	Coupling factors	Operation ongoing
1. Fish escape due to submerged net (28 events, 14 large-scale escapes)			
Collision from foreign vessels Collision from drifted barge Execution failure during net handling Fire damage Floating collar failure Insufficient attachment of the net Latent failure introduced during maintenance Mooring system failure Net rope breakage Predator invasion Sabotage Structure fails to withstand environmental load Too strong force from wellboat/vessel	Chafing due to extra equipment Failures in electric cabinet Erroneous dimensioning Mooring chain breakage Too heavy biofouling on the net Too heavy icing	Storm Strong current	Net replacement No operation Vessel manoeuvring in fish farm Wellboat-involved operation
2. Fish escape due to holes in the net (397 events, 38 large-scale escapes)			
Collision from foreign vessels Contact with mooring system Contact with cleaner fish equipment Contact with delousing skirt Contact with light, monitoring system Contact with mort collection system Contact with other main component (floater) Damage from sinker tube Damage from weight system Design failure Failures in feeding system Fishing gear	Anchor displacement Biofouling Deviation from procedure (contact with structures or weight system) Deviation from procedure (mort collection, float line operation, vessel mooring) Erroneous dimensioning Extraordinary amount of dead fish Installation failure (mounted equipment) Lack of maintenance (mounted equipment, weight system)	Storm Strong current	Crowding of fish Delousing Feed delivery Fish delivery Fish treatment Mort collection Net cleaning Net handling Net installation Net lifting Net repair No operation Sorting fish, lice counting, weighing Transfer fish between cages

Direct cause	Underlying factors	Coupling factors	Operation ongoing
Flotsam Net entanglement with mort collection system Not specified Operational error Predator Production failure Propeller caught in net Service failure Tear from boat collection system Tear from mort collection system Too strong force over stuck float line Too tightened float line tears the net Truck collision Vessel mooring line not in place Wear from weight system	Latent failure after operation (feeding system) Loosened mooring Manoeuvring failure Net entanglement (bottom weight system, float line) Net entanglement with wellboat Not specified Sharp edges (mort collection system) Side effect from combining use of float line with float ring Slack net Technical failure (mort collection system, weight system) Wellboat operation failure		Wellboat-involved operation
3. Fish escape due to loss of fish (68 events, no large-scale escapes)			
Loss from mort collection system Net failure (too large mesh) Operational error	Communication failure Deviation from procedure Erroneous dimensioning Slips and lapses	Strong wind	Crowding Delousing Fish delivery Mort collection Net handling Net shifting No operation Not specified Sorting fish, lice counting, weighing Transfer fish between cages
4. Fish escape due to structural damage without damage to the net (9 events, no large-scale escapes)			
Collision from foreign vessels Collision from operation-related vessels Mooring system failures	Environmental forces Installation failure Maintenance failure Technical failure		No operation mentioned

4.1.2.3 Fish escape scenarios

The fish escape scenarios summarise the most frequent chains of events derived from the Fdir registrations of fish escape events. The hazardous events listed in Table 3 are the top events, and the underlying factors and direct causes in Table 4 are the second and third level of these scenarios. It is important to understand how the underlying and coupling factors influence the direct cause and contribute to the hazardous event for the design and implementation of effective safety measures and barriers for prevention and mitigation of accidents.

Figure 12 reproduces one of the fish escape scenarios presented in article 1, which is scenario *2ai: Wear and tear from structures causes holes*. The figure shows the hazardous event on the top, the identified direct causes are illustrated at level two, and level three shows the underlying factors. The fourth level at the bottom contains risk-influencing factors, which are called coupling factors in article 1. These are weather (wind, storm, precipitation etc.) and sea-state parameters (waves, currents) and are included when they have been mentioned in the escape event registrations, However, the database rarely indicates whether an environmental factor is a coupling factor to an escape accident.

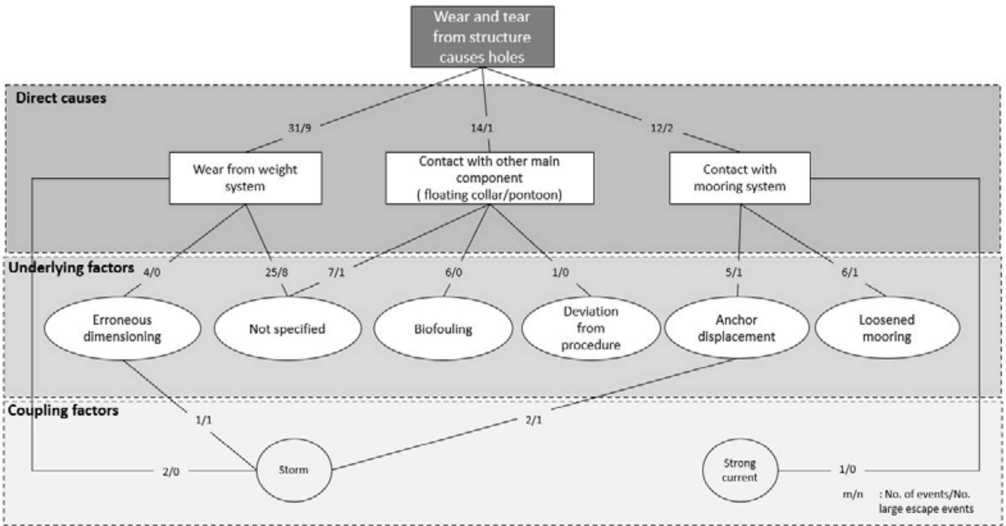


Figure 12 Fish escape scenario 2ai: Wear and tear from structures causes holes. Reproduced from article 1, Yang et al. (Under review).

4.2 Objective 2: Organisational and human factors

The second objective (O2) was to study the anticipated influence from organisational and human risk-influencing factors on fish escape events. The "human factor" or "human error" has occasionally been pointed to as the main cause for fish escapes, which incriminates the workers. This has grave consequences for the workers' own safety in that the fish farmers do whatever they can to avoid fish escape. The workers' motivation to "save the day" results in self-induced occupational hazards (Størkersen, 2012).

Article 2 is the main contribution to objective 2 (Thorvaldsen et al., 2015). Articles 1 (Yang et al., Under review) and 5 (Holmen et al., 2021) contribute to the objective by illustrating the importance of including these factors in the analyses of hazardous events (Figure 13).

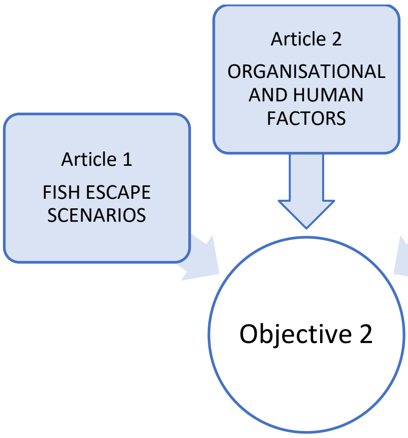


Figure 13 Article 2 is the main contribution to objective 2, and articles 1 and 5 illustrate the importance of these factors in the chain of events.

4.2.1 O2: Data material and analyses

The Fdir fish escape database focuses mainly on external and technical causes and operational failures. The contributing, often underlying, organisational and human factors are not systematically reported or registered. The aim of article 2 is therefore to identify in-depth information about the presence and influence of organisational and human factors in the causal chains of confirmed, large-scale escapes, from the operational manager's and fish farmers' view.

The study is based on qualitative data using three different methods for collection. The main data source in article 2 is semi-structured interviews with twelve workers recruited from companies having experienced a fish escape accident between the years 2009 to 2012. The companies were initially identified through a public registry of fish escape events and the study included informants on fish farms, wellboats, and service vessels. The companies were selected according to the following criteria: having reported a confirmed fish escape, sited in different geographical regions along the Norwegian coastline, companies of different size, and fish farms of both steel construction and net cages with plastic floating collars. The informants were interviewed either in person or by phone. The second source of information is thirty-three nonconformity reports regarding escapes and no escape events made available to the researchers by the companies in the study. A workshop gathering twenty-one participants, trade union representatives, operators, and managers from different fish farming companies is the third data collection activity in the study. The workshop focused on identification of hazards and hazardous events associated with fish farm operations of high escape risk, as learnt from the interviews.

The data material is analysed for information on causes and conditions linked to previous escape events. Due to the objectives of the study, the influence of organisational or human factors on the chain of events is given special attention in the analyses.

4.2.2 O2: Results

The study in article 2 systematically explores the meaning and extent of the term "human error" in the context of fish escape events. The analyses identify the following organisational and human factors which have influenced the development of previous fish escape accidents (Thorvaldsen et al., 2015):

- Technology design, human-technology interaction
- Physical work environment
- Workload and work pressure
- Training, skills, and experience
- Cooperation and communication
- Safety management
- Procedures
- Risk assessment
- Nonconformity reports

This study shows that "human errors" can be linked to a range of contributing causes and conditions, few of which are the responsibility of the worker alone but instead a function of the company's level of performance regarding risk management. The fish escape scenarios in article 1 include direct causes and underlying factors which are organisational or human factors, e.g., "operational error," "installation failures," "deviation from procedure," and "lack of maintenance." The BN developed in article 5 includes organisational conditions and operational errors as individual nodes in the causal chains.

Article 2 also concludes that there is a need for increased attention to how safety is organised in fish farm companies. It is important to understand how organisational factors and conditions influence safety levels in aquaculture operations. This was further explored in the researcher project "Safer operations and workplaces in fish farming" (Thorvaldsen et al., 2021). But how do we *measure* the state of the organisational factors of importance? This is investigated in the study described in the next section.

4.3 Objective 3: Evaluation of OSC method in aquaculture

The safety management system in an organisation should support good safety practices. Appropriate audit methods are necessary to systematically assess the state of these practices. This was the background for objective 3 (O3): to evaluate whether the Operational Safety Condition (OSC) method from the oil and gas industry is applicable to fish farm operations.

Article 3 (Holmen et al., 2017a) is the main contribution to O3 (Figure 14). Article 2 contributes with increased knowledge on the organisational and human factors which influence the development of fish escape accidents (Thorvaldsen et al., 2015).

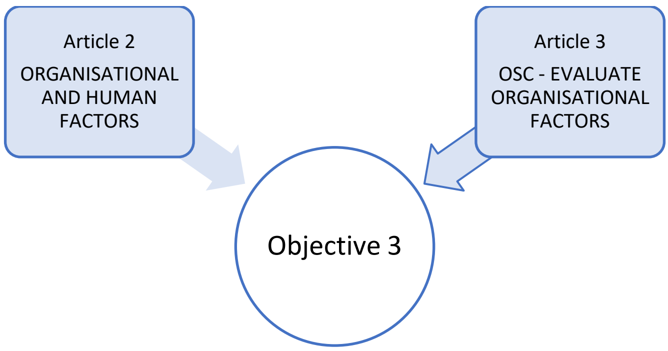


Figure 14 Article 2 and 3 address objective 3.

4.3.1 O3: Data material and analyses

Article 3 is based on information from different sources so as to compile the necessary data material for evaluating whether the OSC method is suitable for the fish farming industry. Publicly available documentation on the development of the original method was studied (Vinnem et al., 2007; Kongsvik et al., 2010; Kongsvik, 2013) as a starting point.

To document the need for a method to audit organisational factors in the aquaculture industry, mandatory requirements on safety management were identified from the relevant laws and regulations (cf. Section 2.2).

Documentation on operations, hazards, causes, factors, and conditions associated with increased risk for fish escape were collected from article 2, Fdir's public escape registry, and previous research (Fenstad et al., 2009; Jensen et al., 2010; Sandberg et al., 2012; Størkersen, 2012).

4.3.2 O3: Results

Safety management and safety audits are regulatory requirements in all Norwegian industries, fish farming included. As of today, fish farms perform internal audits, as required by the internal control regulations, or external audits by a third party. The OSC method could provide an additional tool for companies' internal audits to identify and understand the organisational factors influencing operational safety levels.

OSC was developed to reduce the major accident risk at offshore installations, specifically to prevent release of hydrocarbons (Kongsvik et al., 2010). In O3, the method is applied on unintended release (escape) of farmed fish. Article 3 presents a study carried out step by step to adapt the OSC method to fish farming. The method follows the below suggested steps:

Step 1 – Identify causes of accidents
Step 2 – Map work operations associated with increased risk of escape
Step 3 – Identify organisational factors of importance
Step 4 – Identify internal and external requirements
Step 5 – Define checkpoints
Step 6 – Conduct the audit

Steps 1 and 2 were conducted using the data sources listed in the previous section. The organisational and human factors identified in article 2 (cf. Section 4.2.2) are almost identical to the factors originally established for the oil and gas industry (Kongsvik et al., 2010), which indicates that the latter may apply also to the fish farming industry. Step 3 was hence approached by assessing the seven original OSC factors against the operational challenges described in article 2, and Table 5 summarises the result.

Table 5 The influence of organisational factors in critical fish farm operations. The table is based on a figure in Holmen et al. (2017a) (article 3).

Organisational factors identified in the development of the OSC method	Operations associated with increased risk for fish escape (step 2)	Organisational factors relevant for the operations, cf. column 1 (step 3)
1. Work practice 2. Competence 3. Procedures and documentation 4. Communication 5. Workload and physical environment 6. Management 7. Change management	Crane operations	1–6
	Delousing with tarpaulin	1–6
	Wellboat operation	1, 4, 6, 7
	Daily work and maintenance (harsh weather)	1–6
	Inspection of mooring lines and net cage	1–3, 5, 6
	Net cage replacement	1–5
	Transfer of fish	1, 3, 4, 6
	Feed delivery	2, 4, 5

The structure of the OSC method is that, for each organisational factor (step 3), a list of requirements is established that are retrieved from internal and external sources (step 4). External sources would be regulatory requirements, and internal requirements are found in internal procedures and ISO publications if the company's policy is to benchmark against international standards. For each requirement, checkpoints are to be determined (step 5). Article 3 contains examples of requirements and checkpoints for the organisational factors *work practice* and *competence*.

Step 6 was not performed within the scope of article 3. However, a master thesis in 2019 describes the development of an OSC audit adapted to aquaculture regulations and operations, which has been tested at a fish farm (Andreassen and Olsen, 2019).

4.4 Objective 4: Status and requirements for risk assessments

Risk assessment is a core activity in safety and risk management. Objective 4 (O4) was to explore the status for risk assessment practices in the Norwegian fish farming industry in relation to regulatory requirements. Initial research revealed that the regulatory framework for operational safety in fish farming is complex (Holmen et al., 2017a; Holmen et al., 2017b). Article 4's contribution to the objective stems from presenting the status of risk assessments in the Norwegian aquaculture industry and suggesting an approach to improve risk assessment procedures according to formal requirements (Holmen et al., 2018) (Figure 15).

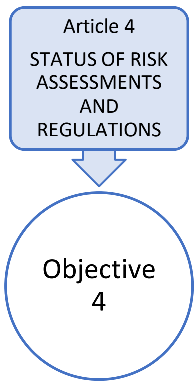


Figure 15 Article 4 addresses objective 4.

4.4.1 O4: Data material and analyses

Data for article 4 is collected from four main sources: 1) review of the mandatory laws and regulations for fish farms regarding clauses on safety and risk management, 2) interviews and observations at five fish farms and on board four service vessels, 3) review of risk assessment documentation from three fish farming companies, and 4) four workshops with participants from several companies in which risk assessments of selected operations were conducted. These operations were rated by the participants to be of "high risk." The overall aim of the analyses was to identify gaps between the current practices and the mandatory requirements for conducting risk assessments. The comparison is based on the recommended procedure for risk assessments according to the Norwegian standard NS 5814 in the version valid at the time of the study (Standard Norway, 2008).

4.4.2 O4: Results

Risk management of fish farm operations is regulated by five authorities (Figure 4): the Directorate of Fisheries (Fdir), the Norwegian Maritime Authority (NMA), the Food Safety Authority (FSA), the Labour and Inspection Agency (LIA), and the County Administration/Governor. Article 4 summarises the mandatory requirements for risk assessments found in the relevant regulations, as well as the current industry practices. The interviews, observations during fish farm operations, and review of risk assessment documentation revealed significant gaps compared to the recommendations in NS 5814.

The main gaps appear in the planning phase in that the risk assessments are not prioritised in the daily work, and there was insufficient involvement of operators in the analysis phase. Involvement of operators is a core requirement also in the internal control regulations which are mandatory for the aquaculture industry (Ministry of Labour and Social Affairs, 1996; Ministry of Trade and Fisheries, 2004). Furthermore, challenges exist regarding implementation of risk assessments in the organisations, i.e., the thoroughness of the risk analysis phase, the quality and content of the risk documentation, and how well the organisation manages to transfer the knowledge from the risk assessments into improved operational safety.

The findings suggest a workshop-based approach for risk assessments which satisfies the requirements in the fish farming industry (Holmen et al., 2017b). Workshop participants are divided into four groups as shown in Figure 16. Each group receives markers of different colours they keep throughout the work. Groups A-D starts to describe, step by step, the tasks of one operation each. When finished, they move to the next table and comment on the description made by the first group. This continues till all four groups have agreed on the description of the operation. The next stage involves identifying the hazards associated with the work tasks, and the same procedure of commenting/adding to the input from the other groups is continued. This is repeated for the next steps of the risk assessment procedure.

Fish farm and service vessel workers should be the main participants of these workshops, hence ensuring a good involvement of operators. The largest improvement compared to the current practices is that each operation first is listed in detail, and the hazards associated with each task are identified, described, and evaluated by the operators. Limited resources in daily operations require efficiency and good planning, and the planning and documentation phases of the risk assessment procedure may be performed by the HSE professionals of the fish farm company.

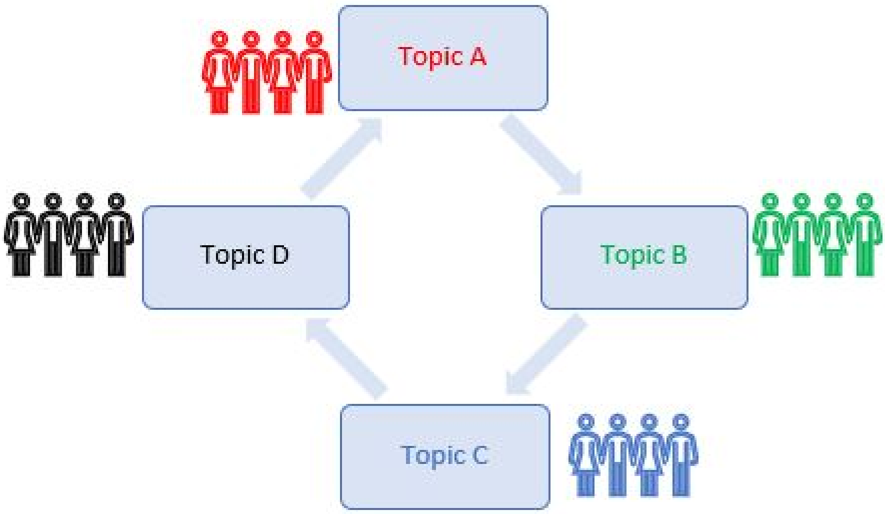


Figure 16 Workshop layout for true operator involvement in risk assessments, according to Holmen et al. (2017b).

4.5 Objective 5: Risk-influencing factors and safety indicators

Objective number five (O5) was to identify and analyse human, organisational, and technical risk-influencing factors and develop safety indicators for reducing risk for fish escape during fish farm operations. Article 5 is the main contributor to this objective (Holmen et al., 2021) (Figure 17). Findings from the research published in article 2 (Thorvaldsen et al., 2015) and article 3 (Holmen et al., 2017a) contribute to O5 through knowledge on the influence of organisational conditions and factors on operational safety. Article 4 (Holmen et al., 2018) contributes with an overview of regulatory requirements and industry best practices regarding maintenance of fish farm structures and monitoring of operations.

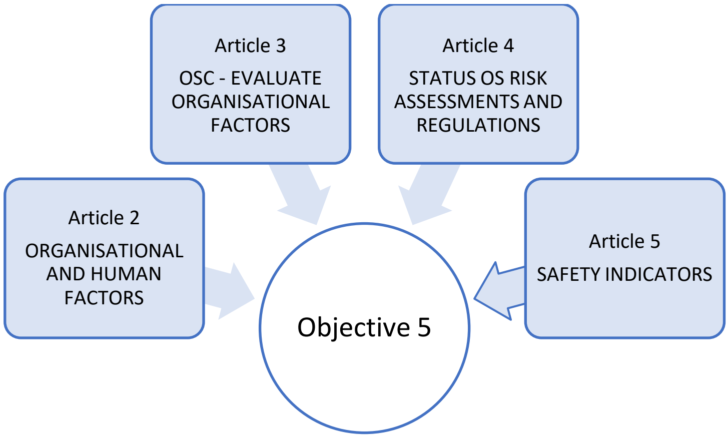


Figure 17 Article 5 is the main contribution to objective 5. Articles 2 and 4 give input to O5 on regulatory requirements and human and organisational factors.

4.5.1 O5: Data material and analyses

The main objective of article 5 was to develop a methodology for identifying safety indicators in fish farming operations using fish escape accident reporting data. The case study in this article is based on a subset of the Fdir database, i.e., confirmed escapes of salmon and trout during the years 2010–2016 limited to the hazardous events "hole in net" and "submerged net." The approach in article 5 entails extracting all environmental, technical, operational, and organisational conditions and hazardous events mentioned in the reported accidents to develop a qualitative BN, thus linking the factors together.

Articles 2, 3, and 4 are sources of information on operations associated with increased risk levels by the fish farm workers, organisational and human factors, and regulatory requirements. Available analyses of causes of escape were used to determine the logical sequence of the causal chains (Føre and Thorvaldsen, 2017; Thorvaldsen et al., 2018; Føre et al., 2019). Based on the insight from the BN, risk-influencing factors (RIF) are identified. Safety indicators are derived to monitor and measure the condition of the RIFs. The final step concerns evaluating the indicators according to chosen quality criteria. Expert judgements have been included as a part of the evaluation based on discussions with three operational managers from the fish farming industry.

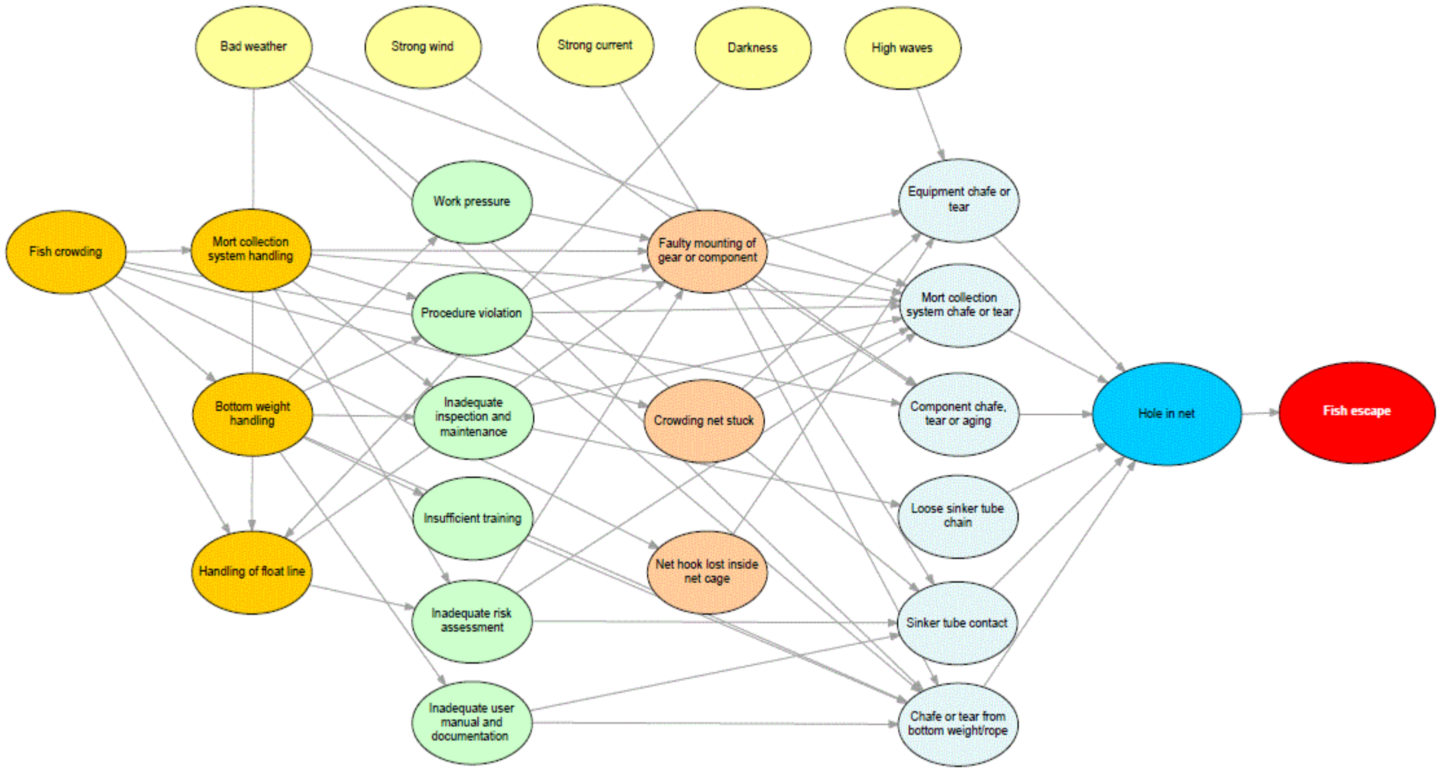


Figure 18 Chain of events for the operation fish crowding and the hazardous event "hole in net". The network is based on confirmed fish escape events in the Fdir database years 2010–2016 (reproduced from Holmen et al. (2021)).

4.5.2 O5: Results

The study resulted in an overview of the causal chains for registered fish escape accidents, a list of RIFs for fish escape events, and suggested safety indicators to measure the condition of each RIF.

4.5.2.1 Causal chains

Figure 18 shows an example of a graphical network based on the fish escape analyses, the BN for the operation fish crowding (reproduced from Holmen et al. (2021)). The causal chains are illustrated with the main operation ongoing as the parent node on the left and the hazardous events and the fish escape node on the right side. The indirect and direct contributing causes and factors are sorted in logical order as interpreted from the accident reports between the operation and the hazardous event. For the case of fish crowding, the hazardous event "hole in net" is the only one registered and thus included in Figure 18.

4.5.2.2 Risk-influencing factors (RIF)

Hazards associated with increased risk levels at fish farms emerge from organisational, operational, and technical aspects, and environmental conditions may also influence risk negatively. Knowledge about the relevant RIFs may form a good foundation for both authorities and the fish farming industry to develop preventive and mitigating measures for fish escape. Table 6 summarises the RIFs identified in articles 2, 3, and 5. In articles 2 and 3, the term *risk-influencing factor* as such is not used, but, according to the RIF definition in article 5 and Section 2.1, the term applies to the conditions and contributing factors identified in these articles. Article 2 focuses on organisational aspects and conditions influencing risk of escape, including technology and physical work environment. RIFs of different types are thus derived from the findings in this study. Article 3 evaluates whether the OSC method originally developed for the oil and gas industry could be adapted to fish farming and hence focuses only on organisational RIFs. Article 5 identifies categories of RIFs and individual RIFs from accident report data (Holmen et al., 2021) as one step in the suggested approach for developing safety indicators.

4.5.2.3 Safety indicators for fish escape safety level monitoring

The safety indicators are the measurable parameters carefully identified to reflect the changes in the condition of each RIF. The final set of indicators are selected according to four quality criteria, which shall ensure that the indicators are observable, quantifiable, relevant, and robust. Figure 19 shows the forty accepted safety indicators resulting from the fish escape case study in article 5. There are ten safety indicators associated with seven environmental RIFs, eleven organisational safety indicators and four RIFs, seven operational safety indicators and an equal number of RIFs, and twelve technical safety indicators and twelve technical RIFs. Article 5 includes suggestions for acceptable states of the safety indicators.

Table 6 A summary of risk-influencing factors (RIF: causes, underlying factors, coupling factors, conditions, aspects etc.) derived from analyses of fish escape events in articles 2, 3, and 5.

Environmental RIFs	Organisational RIFs	Operational RIFs	Technical RIFs
Article 2 Thorvaldsen et al. (2015)			
Physical work environment: Harsh weather Strong winds Strong currents High waves	Workload and work pressure Training, skills, and experience Cooperation and communication Safety management Procedures Risk assessment Nonconformity reports	Handling net Handling sinker tube Lice treatment Vessel-assisted operations	Technology design, human-machine interaction Sinker tube Tarpaulin Net condition
Article 3 Holmen et al. (2017a)			
	Work practice Competence Procedures and documentation Communication Workload Physical environment Management Change management		
Article 5 Holmen et al. (2021)			
Wind Water current Waves Visibility Icing Flotsam Predators	(Adopted from article 3) Workload Work practice Competence Procedures and documentation	Vessel manoeuvring around fish farm Vessel manoeuvring alongside net cage Net attachment procedure Component/equipment installation Crowding net handling Net hook storage Net cage repair service Fish pump mounting	Electric power supply condition Floater condition Feed barge mooring Floater biofouling degree Mort collection system condition Anchor placement Component/equipment technical state Mooring line condition Coupling plate/ crowfoot placement Sinker tube chain state Sinker tube placement Bottom weight system condition

Environmental safety indicators (10)

- Wind speed
- Wind direction
- Water current speed
- Water current direction
- Wave height
- Wave direction
- Visibility distance
- Amount of ice on structures
- Flotsam presence
- Predator presence

Organisational safety indicators (11)

- Ratio of workers available/workers needed
- Number of overtime hours per operator in previous shift
- Number of overtime hours per operator during a rotation
- Proportion of operators reporting that the workload often/very often is too high
- Number of registered procedure nonconformities per year (per work operation)
- Proportion of operators describing a work practice corresponding to the documented procedure
- Backlog of safety-critical maintenance/inspections (there are postponed tasks)
- Proportion of operators with documented qualifications that meet requirements
- Risk assessments documented
- Number of registered failures due to inadequate user manual
- Updated documentation for critical equipment and main components

Operational safety indicators (7)

- Number of undesirable vessel contacts with critical fish farm structures per month
- Missing knots detected
- Incorrectly mounted component or equipment detected
- Crowding net gets stuck during the operation
- Lost net hook inside net cage during fish crowding
- Faulty net repairs detected during a production cycle
- Faulty fish pump mountings detected during or after fish transfer

Technical safety indicators (12)

- Detected failure in electric power supply
- Defective floater elements detected
- Barge mooring failure detected
- Heavily biofouled floaters detected at fish farm
- Detected failure in mort collection system
- Ratio of detected anchor displacements/anchor checks
- Ratio of detected failures/component checks
- Ratio of detected failures/mooring line checks
- Ratio of detected failures/coupling plate/crowfoot checks
- Ratio of loose sinker tube chains/sinker tube chain checks
- Ratio of detected failures/sinker tube placement checks
- Ratio of detected failures/bottom weight checks

Figure 19 The safety indicators from the case study in article 5 (Holmen et al., 2021).

4.6 DISCUSSION AND EVALUATION OF CONTRIBUTIONS

Table 7 summarises the PhD project. The contributions to the overall aim of the thesis are discussed in the following subsections in terms of scientific and practical applications.

Table 7 A summary of the PhD project.

Objective	**Summary**
The main objective of the PhD project is to develop knowledge and methods for improved safety management in exposed sea-based fish farming.	
O1. Analyse fish escape event data and identify hazards and fish escape scenarios which may develop into hazardous events.	• Fish escape data registered by Fdir was explored for information on hazards and contributing causes. The analyses included both confirmed escapes (accidents) and no-escape events (incidents). • The original categorisation of the Fdir database was not suitable for capturing the complex causality or the most frequent fish escape scenarios. • A new categorisation system was developed. The registered fish escape events were reanalysed and re-categorised into i) hazardous event, ii) direct causes, iii) underlying factors, and iv) coupling factors. • The reanalysis of the fish escape data made use of the free-text field and previous analyses of fish escape events to clarify causal chains. When possible, the ongoing operation (if any) was identified. • New categories of hazardous events were identified. Four main groups of hazardous events were established: fish escape due to 1) submerged net, 2) holes in the net, 3) loss of fish, and 4) structural damage without damage to the net. Groups 1 and 2 consist of three and thirteen hazardous events respectively, which reflects the failure mode of each fish escape scenario. Scenarios 3 and 4 are not broken down further. • The fish escape data was reanalysed using the new categorisation system according to the consequence of the event (size of escape). 502 out of 745 events were reanalysed due to lack of data for some events. The most frequent hazardous event is "holes in the net," which are most often caused by net chafing by equipment/structures or operational failures. Thirty-eight out of 397 escape events categorised as "holes in the net" were large scale. • Fish escape scenarios were drawn based on the reanalysis of the Fdir database with the hazardous event as the top event, direct causes at the second level, and contributing causes at the third. Coupling factors were illustrated as the fourth level of the scenarios. • By including all events, the most frequent hazards and causes are captured regardless of consequence. Some scenarios may result in more severe escapes if the influence of the underlying or coupling factors were stronger.

Objective	Summary
O2. Analyse the influence of organisational and human factors in fish escape accidents.	• The Fdir fish escape database contains scarce information on organisational and human factors. The main source of information for this study integrated interviews and a workshop with operators and managers in fish farming companies. • The term "human error" was systematically explored and specified in the context of recent fish escape accidents experienced by the informants. Nine organisational and human factors which influence fish escape accidents were identified (cf. section 4.2.2). • The operations associated with increased risk for fish escape were i) net and sinker tube/weight system handling, ii) delousing operations, and iii) vessel-assisted operations. These operations are also associated with elevated occupational risk levels. • The findings documented a need for increased attention to the organisation of safety in fish farming and increased knowledge on how organisational conditions affect operational safety levels.
O3. Evaluate whether the Operational Safety Condition (OSC) method from the oil and gas industry is applicable to fish farm operations.	• All Norwegian companies are required to implement HSE management systems. Internal audits are required by the Internal Control regulation (statutory by the Working Environment Act) and aquaculture legislation. • Currently, no systematic evaluation of operational safety in terms of organisational conditions in the fish farming industry exists. • The OSC method, originally developed for assessment of operational safety levels in the oil and gas industry, was adapted and evaluated for use in the aquaculture industry. • The starting point is one type of hazardous event or accident associated with high operational risk. In this study, fish escape was selected. • A six-step approach was suggested to adapt the OSC method and develop relevant checkpoints for an audit at a fish farm. • The seven organisational factors from the original OSC were found relevant also for fish farm operations (cf. Table 5).
O4. Explore the status for risk assessment practices in the Norwegian fish farming industry in relation to the regulatory requirements.	• The aquaculture production must comply with safety requirements within the legislative areas of five regulatory authorities. • There are mandatory requirements for risk assessment of fish escape, the technical condition of a fish farm, vessel design and operation, environmental risk, occupational risk, fish welfare and health, and food safety. • The technical standard NS 9415 for fish farm structures refers to NS 5814 for a standardised procedure for risk assessments. The current practices differ significantly from the recommendations in NS 5814 on several points. • The quality and documentation of risk assessments vary considerably across the industry.

Objective	Summary
	• Involvement of workers is a core requirement also in internal control regulations., but true involvement is to a large extent lacking. • To close the gaps, a new approach which satisfies the requirements was suggested. The basic idea is to gather personnel to a workshop and involve them in the core steps of the risk assessments: describe the work procedure in detail and agree on a best practice, hazard identification of the tasks, analyse causes and discuss consequences, and suggest preventive and mitigating measures. • Risk assessments should be based on the operations carried out at the fish farm. This will provide an overview of the hazards associated with the work tasks and factors influencing risk levels (environmental parameters, the operators' competence, available technology/equipment, the condition of the structures involved, etc.) • Companies should develop risk assessment templates for their yearly updates to be adapted to each vessel or fish farm. However, the templates should be based on strong involvement of workers in accordance with the previous recommendations.
O5. Identify human, organisational, and technical risk-influencing factors and develop safety indicators for reducing risk for fish escape during fish farm operations.	• There is little available knowledge about the factors that influence risk levels during fish farm operations. • Safety indicators may be useful for monitoring performance related to organisational, operational, and technical safety at the fish farm over time, support decision-making, and detect the need for risk-reducing measures during operations. • A six-step method for identification of operational safety indicators was developed and tested. • The case study was fish escape due to the hazardous events “hole in net” and “submerged net.” Causal factors and conditions were extracted from the Fdir escape event data and sorted into categories of organisational, operational (instead of human), technical, and environmental factors (step 1). • Information was gathered on the ongoing fish farm operations connected to the hazardous events (step 2). • A BN was drawn to illustrate the causal chains and the complexity of the development of fish escape accidents (step 3). • Thirty-one organisational, operational, technical, and environmental RIFs were identified based on the BN (step 4). • Forty-one safety indicators were developed based on the suggested approach (step 5). • Forty indicators were accepted after evaluation according to the chosen quality criteria (step 6).

4.6.1 Theoretical contributions

The research in the PhD project was designed to contribute to safety in the fish farming industry. The contributions in this section target the scientific community, the authorities, and the industry level.

The use of scenarios as a basis for fish escape risk reduction strategies is novel in the fish farming industry. The scenarios in article 1 are developed based on the Fdir fish escape database, including all registered events of salmon and trout escapes regardless of consequence.

The new categorisation system (hazardous event, direct cause, underlying factors, and coupling factors) is not linked to a specific technology and may hence be applied for any sea-based fish farm design, including offshore fish farms. The fish escape scenarios capture the complexity and levels of the causal chains. For one hazardous event, several direct causes and associated multiple types of underlying factors may be included in one scenario, as opposed to analysis of separate sequential chains. The scenarios provide a basis for identifying low-performance or lacking safety barrier functions and how to prioritise resources in emergency planning. The scenario approach is generic and could be applied to other types of accident analysis as well, e.g., occupational injuries or threats to fish health.

Integrating the new categories into the escape reporting system would direct the operational manager to investigate the causes of the event. These fields should not be optional to fill in. To include RIFs of all relevant types, the reporting form should ask for this in the explanatory text. This approach would improve the quality of the fish escape registry and make it a more reliable tool for Fdir to monitor the need for improved preventive measures in the industry. The increased learning from the hazardous events may also benefit the aquaculture industry and result in improved procedures and integrated safety barriers in new technology designs.

"No-escape events" comprise 60% of the registrations in the Fdir database and had previously not been included in causal analyses—neither by researchers nor Fdir. The inclusion of these events provides a larger data source for identifying the most frequent hazardous events and scenarios. This may contribute to the prevention of the less frequent, more serious escapes, which might evolve if the influence of the underlying or coupling factors were stronger. This is in accordance with Bellamy (2015), who analysed a large database of occupational accidents and found that, for the *same* hazard categories, a correlation exists between the causations of more frequent, smaller consequence accidents and the major accidents. This implicates that the performance of the preventive and mitigating measures (safety barriers) should be monitored to control the hazards or hazardous events. The fish escape scenarios contribute knowledge on how the underlying and coupling factors influence the development of the hazardous event.

There are currently few means for assessing and monitoring safety levels in the aquaculture industry. This study's results document that risk-influencing organisational conditions need to be investigated. The reporting of fish escape events, including both confirmed and suspected escapes, are mandatory, but the focus has historically centred on the technical and structural causes. Systematic documentation on the industry's performance according to the organisational factors will add useful information for the authorities' and industry's campaigns to reduce the risk of fish escape. A suggested approach is to apply the OSC method to develop an audit scheme on an industry level, which includes all regulatory requirements, industry standards, and best practice fish farm operations.

A preliminary study of the OSC method applied to the aquaculture industry showed that it could be a useful tool for internal audits of organisational safety conditions in fish farm operations with elevated risk for fish escapes (Holmen et al., 2017a). However, the audit was not performed (step 6 of the method). A follow-up study on development of an OSC audit scheme has been conducted by two master students at NTNU in cooperation with a salmon farming company (Andreassen and Olsen, 2019). Their OSC audit was limited to three organisational factors: competence, communication, and procedures. Thirty-five requirements and seventy-eight checkpoints were identified in accordance with both external and internal requirements from the company and industry regulations. Ten informants were interviewed at one fish farm. The company management acknowledged the value of assessing the safety management practices using the OSC method, and the results of the audit demonstrated a strong agreement between requirements and practices. However, the method is resource-demanding, and it therefore may not be feasible to allocate the time and cost needed to conduct a full audit in a fish farming company. The participants in the audit regarded the OSC method as valid, reliable, and adequate for the fish farm operations.

Gaps appear between current practice and regulatory requirements for risk assessment. The results show that companies would benefit from a higher degree of standardised practices across the industry. A holistic framework for safety management in fish farming, including the five risk dimensions in one system, would be recommended on an industry level for use by both regulators and company actors. The operations associated with high risk for fish escape are also associated with occupational risk (Thorvaldsen et al., 2015). The preventive work could be more efficient if measures were designed to manage all relevant risks.

Risk assessments are, at present, mainly performed during the production phase of a fish farm. If the future operation modes were planned and risk assessments performed during the design phase, safety barriers could be integrated into the technological design to a higher degree. Today's practice involves implementing procedures for safe handling of hazardous equipment rather than designing equipment that is inherently safe.

The risk picture and levels at the fish farm are likely to be different during periods of normal operation compared to periods of a certain activity, e.g., maintenance operations or fish crowding (Yang and Haugen, 2015). This difference should be taken into consideration when implementing and prioritising preventive and mitigating measures. The new knowledge provided on hazardous event scenarios, RIFs, and causal chains may contribute to assessment of activity-related risk and evaluation of the need for additional safety barrier functions at the fish farm during operations.

4.6.2 How can the fish farming industry benefit from this research? Practical applications

This section focus will focus on the employees, who are part of the organisational units "fish farm" and "service vessel," to exemplify how the results from the PhD project can contribute to safer operations in compliance with regulations.

The evolution of Norwegian fish farming into a high-tech industry coincides with the development of modern safety theories and models, as well as an increasing attention to safety management from the regulatory authorities (Kongsvik et al., 2018a). Nevertheless, it seems as if fish farming has inherited some of the safety challenges from the agricultural and marine industries (Holen et al., 2018b). The workers at the fish farms and on the service vessels perform a range of manual tasks and make decisions which influence the success of the operation both in terms of getting the job done and overall operational safety. The humans are the hub in the fish farm operation system but are also perceived as the weak link of the same. The research activities provide an improved understanding of fish farm operations and the hazards and conditions increasing the risk for fish escape. Furthermore, the results include generic methods for scenario analysis of accidents and incidents, analysis of underlying factors, and identification of RIFs. The organisational and human factors influencing safety in operations, in particular user-friendly and safe design, work environment, communication, competence, and communication, should be considered in revising and improving both routine and specialised work operations, as well as work schedules, to reduce work pressure and increase involvement in safety-related decisions.

Risk assessment is mandatory to perform for several risk dimensions at fish farms and lays the basis for systematic actions to improve safety management. The research activities show that companies find it challenging having to answer to several authorities, which may have different preferences in how the risk documentation should be presented. This fragmentation in the authorities' regulations and inspection routines may result in equally fragmented risk management systems which satisfy the inspectors but do not adequately reflect the risk levels in the operations. This was the motivation for suggesting an improved approach to perform high-quality risk assessments at the fish farms which might reduce the possible conflicting objectives. Risk assessments should ideally be performed with the operation as the starting point, and all relevant risk elements associated with the tasks should be included, taking all relevant risk dimensions into consideration. The range of hazardous events and RIFs identified during the different parts of the PhD project supplement the basis for risk assessment of fish farm operations.

The time between fish generations is already packed with clean-up and maintenance tasks, but this still is the best period to allocate time for risk assessment updates involving all workers. Fish farm personnel should be involved in risk assessments to become familiar with the hazards in their work environment, and doing so is also a requirement in the internal control regulations (Ministry of Labour and Social Affairs, 1996; Ministry of Trade and Fisheries, 2004). To save time, operators should be involved only in the most critical stages of the risk assessment process, the ones which they also know best. These stages constitute describing the operation and work tasks in detail; identifying hazards, causes of hazardous events, possible consequences; and suggesting actions for prevention and mitigation of the identified risks. The approach needs to be engaging, perceived as relevant to the participants and "worth the time spent," understandable, and be directly related to the work tasks. This would also ensure true involvement of the operators according to the regulations (cf. Section 4.4).

The recommended procedure for improved risk assessments may contribute to establishing well-proven, quality-assured procedures at fish farms. As already described, one step in the process is to specify the work operation to be assessed and relate the identified hazards to the tasks performed, competence needed, and equipment and components involved. An additional output of this process is hence a thorough description of the operation and the conditions required to perform it safely, which is validated by the participants in the workshop.

Once established and validated, preferably as a result of workshops with experienced operators, standardised procedures may be used for training and decision support for less-experienced personnel. Last year, one Norwegian fish farm company reported to have hired the youngest farm manager ever. This manager is responsible for a team of fish farmers, as well as approximately two million fish (Finnmark Dagblad, 2020). There is no doubt of this young fish farmer's motivation or practical or managerial abilities; however, there is a limit to the amount of experience a person in their early twenties can have gained during a relatively short professional work life. On the other side, this person does have several years’ experience working at fish farms. This may not be the case for other employees. The aquaculture industry has been fast growing and has hired staff with little or no experience in fish farming or other marine workplaces. This enhances the need for best practice procedures for safety management and operations which can be adapted to each fish farm's equipment and choice of structural design.

The list of RIFs identified from the Fdir escape database can also be used for learning purposes at the fish farms, both for making newcomers in the occupation aware of potential hazardous events as well as input to risk assessment updates. Implementation of a safety indicator program would help the fish farm manager to detect decreases in safety levels at an early stage, either during daily operations or when preparing for operations associated with increased risk levels. Ideally, the suggested method to develop safety indicators should be applied to all risk dimensions present and thus provide a dynamic supplementary tool to risk assessments and SJA for complex operations.

The specialisation of work operations within dedicated crews is likely to reduce the risk of failures during operations, as the crews will be experienced with these types of operations, and this practice is becoming more common in the aquaculture industry. On the other hand, this introduces out-sourcing at the fish farm, which may challenge safety because the hired service crew may not meet the same standards regarding safety performance. This has been mitigated by the fish companies by implementing safe job analyses (SJA) prior to operations, which is regarded as safety-critical for fish welfare, fish escape, and personnel. These operations are characterised by the involvement of several vessels and crews, crane operations, fish treatment, and handling of net cage structures and/or hazardous chemicals. The SJA should involve all personnel to update everyone on the communication lines, responsibilities, and preventive and mitigating actions necessary to maintain safety in operations. Hazards and RIFs that were identified from analyses of hazardous events during previous operations would provide relevant input to checklists for SJA.

Hazards and RIFs for fish escape, as well as hazardous events related to the other risk dimensions in fish farming, can be used as a basis for systematic risk assessments of the operations at the new fish farm concepts. Knowledge about what may go wrong should also be reflected during the development of safe operational procedures, as well as consideration of the competence requirements of operators. Some of the hazards may not be relevant, but the basic functions need to be in place regardless of the fish farm design: access to fish farm by personnel, acceptable work environment and living quarters, daily operation and regular maintenance of fish farm structures, fish feed deliveries, feeding of fish, daily monitoring of fish welfare and health, delivery of smolt, possible treatment of fish, delivery of fish for slaughter, and mort collection and destruction.

Safety management implies both accident prevention and mitigation, i.e., consequence reduction. Mitigating activities have traditionally dominated over preventive because it takes a lot more effort to implement preventive barriers. A recent study compared the resources spent for incident prevention and accident mitigation (Puisa et al., 2021). The authors regretted that they could not conclude firmly one way or another due to poor data quality, but the results do indicate that prevention is more cost-effective than mitigation with respect to investments. Efforts should hence be increased to implement preventive safety barriers. The type of barrier needed may not be as obvious if the causal chains are complex. However, applying systematic methods to identify RIFs and causal chains, as demonstrated in this PhD project, may provide the necessary knowledge to design and implement effective safety measures.

4.6.3 Governance of the Norwegian aquaculture industry

Some have suggested establishing an "Aquaculture Directorate" to become the overarching authority coordinating all elements of aquaculture activities in Norway (Almås and Ratvik, 2017). For comparison, the Petroleum Safety Authority in Norway (PSA) is a government supervisory and administrative agency with regulatory responsibility for safety, the working environment, emergency preparedness, and security in the petroleum sector (PSA Norway, 2019b). It has a coordinating function for supervisions across several technical and operational areas of oil and gas production, including the work environment regulatory requirements. PSA is responsible for administrative decisions regarding the O&G industry, e.g., consents, orders, fines, and shutting down operations. PSA is also a directorate, which in the Norwegian context is a body responsible for developing, managing, and communicating knowledge connected to their area of technical expertise. PSA reports to the Ministry of Labour and Social Affairs and serves the Ministry, other governmental bodies, and the public with expertise regarding the petroleum sector.

One "umbrella" authority might also benefit the organisation of safety because risk management requirements would be coordinated and not fragmented like they are today (Holmen et al., 2018; Holen et al., 2019). However, for the time being, the industry operates in accordance with requirements from several regulators.

5 CONCLUSION AND FURTHER WORK

5.1 CONCLUDING STATEMENTS

The potential exists for improving safety in aquaculture operations, both at present sites and future, more exposed locations. The fish farming industry faces several challenges which need to be addressed on different managerial and operational levels. The research and results presented in this thesis target aspects of safety management and what the fish farming companies can do in practice to increase safety in operations, mitigate hazardous events, and prevent accidents, i.e., how to improve their safety management in daily operations. Fish escape has been used as the case throughout the PhD project.

Hazardous events associated with fish escape have been analysed according to a new categorisation system which sorts the causal chains into four levels: hazardous event, direct cause, underlying factors, and coupling factors. Fish escape scenarios are identified based on these categories and illustrated as influence diagrams. The scenarios may be used to design and implement effective risk-reducing measures.

Fish escape registrations by Fdir have traditionally focused on technical and external causes and failures in operations. The influence of organisational and human factors in fish escape accidents has been explored in a qualitative study. The findings show that causes reported as "operational errors" or similar mainly represent a range of organisational factors related to the safety management performance of the fish farming company.

The safety practice in a company needs to be audited using appropriate methods currently not implemented. The evaluation of the Operational Safety Condition (OSC) method, originally developed for the oil and gas industry, showed that it is applicable for measuring the state of organisational factors in the aquaculture industry. However, the method is resource-demanding for individual companies, and it is recommended to be further developed as a joint industry initiative.

There is a gap between the current risk assessment practices in the Norwegian fish farming industry compared to the regulatory requirements. A workshop-based approach for conducting risk assessments is recommended to achieve operators' active involvement. Five authorities regulate the requirements for risk management in fish farming, and this contributes to a fragmented safety management system in that different risk dimensions are treated separately. A holistic approach to safety management is recommended to improve the efficiency of prioritising and implementing safety measures.

The industry could benefit from developing best practices for complex operations. Establishment of best practice procedures is an added value of the risk assessment workshops. Such procedures should not replace the mindfulness of experienced operators but represent the best practice under normal operating conditions. A set of standardised procedures and equipment may also reduce the possible conflicts and competence gaps when personnel are hired from other locations, as less time would be devoted to familiarising themselves with the new location.

Safety indicators may have the potential to be a yet missing decision-support tool in safety management in fish farming. As an intermediate step in the suggested method to identify indicators, causal chains for registered fish escapes are identified and described. The influence of environmental, organisational, operational, and technical RIFs on the main hazardous events causing fish escape is illustrated in a qualitative BN. Safety indicators are developed and selected to reflect the condition of each RIF. Safety indicators may be used to monitor the trends in safety levels at the fish farm, in the company, or at the industry level if implemented as an industry standard. The knowledge regarding RIFs and hazardous events may also be used as input to risk assessments and SJA checklists, as well as training of fish farm personnel.

5.2 FURTHER WORK

The registrations in the Fdir database capture mainly technical factors in a one-dimensional causal chain. Additional causal analyses on human, technical, and organisational contributing factors suggest multiple cascading chains of events, as illustrated by the BN in article 5 (Holmen et al., 2021). Converting these complex causalities into a valid, quantitative risk model implies aggregation and simplification of causalities. Important RIFs may hence be lost in a quantitative risk model. Furthermore, calculating reliable probabilities for the interactions in the BN would require access to detailed data on frequencies and contributing factors for each fish escape incident. These data are, for the time being, unavailable. Another approach is to further develop the BN into an object-oriented Bayesian network, which previously has been applied to ecological risk modelling of hydrocarbon release in the Arctic (Sajid et al., 2020). This approach could be tested for the fish escape scenarios with input from the detailed analyses of RIFs for fish escape.

The aquaculture industry would benefit from strategies for safety and risk management which capture emerging hazards independently of detailed design. The experience from the current fish farm designs needs to be transferred to concepts for more exposed or offshore fish farming in a systematic manner, similar to the practice in the oil and gas industry for offshore oil production units (Kjellén and Albrechtsen, 2017). In the planning phase, the current knowledge of hazardous events and fish escape scenarios, contributing causes, and RIFs can be used as checklists to assess the need for improved barrier functions—either operational, organisational, or technical (PSA Norway, 2017).

As much as possible, barrier functions should be integrated into the design to reduce the need for the operators to perform special safety procedures.

Furthermore, the operation of future fish farms should ideally be planned in the concept development phase to assess possible operational risks. The need for safety measures for personnel, fish, or farm structures could be captured at this stage and reported back to the engineers. As of today, the main responsibility for the knowledge transfer is laid on the technology developers and each fish farm company. A common effort in the aquaculture industry, guided by the regulatory authorities, is likely to speed up the implementation of measures for improved safety in aquaculture operations.

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Part II Articles

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The escape of fish from Norwegian fish farms: Causes, risks and the influence of organisational aspects

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ABSTRACT

The escape of fish from fish farms is a problem for the Norwegian aquaculture industry. Following a decrease in structural equipment failures, human errors and human factors have been highlighted as one of the main challenges when it comes to preventing fish escape. This article identifies causes of previous accidents leading to fish escape, as well as risks of escape, focusing in particular on the organisation of work as well as the role of the workers at fish farms. It is apparent that operational managers and fish farmers have great responsibility when it comes to preventing escape. Severe consequences for individuals and companies if fish escape may lead to workers prioritizing the safety of the fish over their own safety. Accident causality is often complex. The term "human error" may be perceived as incriminating by employees, as it focuses on the individual and not the bigger picture.

1. Introduction

In April 2013, during lice treatments of farmed salmon, around 13,000 salmon escaped from a Norwegian fish farm. The accident happened when a well boat moved fish from one net cage to another. Fish were pumped on board and transported to the new cage. While pumping the fish into the new net cage it soon became apparent that the net was put up incorrectly; with no physical barrier preventing the fish from swimming out into the sea. The company in question stated that the accident was caused by human error [1].

Escape of farmed fish is a challenge for the Norwegian aquaculture industry. Farmed salmon is seen as a threat to biodiversity because it disrupts wild salmon gene pools [2]. Consequently, escape of fish harms the reputation of the industry. As illustrated above, human error stands out as one of the main causes of escape in recent years. Following the introduction of formal regulations, workers may face severe sentences if found responsible. Fish farmers and operational managers thus have a great responsibility when it comes to preventing fish escape at farm sites.

The objective of this article is to identify causes for previous escape of fish, focusing in particular on organisational aspects and the role of workers at fish farms. This articles aims to answer the following questions: "Which aspects contributed to earlier escape incidents and near incidents?" and "Do organisational aspects influence the risk of fish escape? If so, how?" A descriptive approach provides knowledge specific to the Norwegian aquaculture industry that may help prevent fish escape in the future.

2. Norwegian aquaculture

Aquaculture is a leading export industry in Norway. In addition to providing food, it provides jobs and spin-off effects that are of great importance to the local and national economy. Currently about 4000–5000 people work in different parts of the industry. Marine industries are seen as essential for future value creation and employment, and aquaculture has been identified as the sector with the largest potential for growth [3–5].

The main species in Norwegian aquaculture are Atlantic salmon and trout. Fish are bred in net cages at fish farms along the coast. To ensure water quality and reduce impact of farm wastes, modern farm sites are located in partly sheltered areas away from the shore [6]. Fish are transported by well boats from land-based hatcheries to farm sites. They are kept in net cages until reaching desired weight. This usually takes around 18 months. Well boats then transport the fish back to land for slaughtering and further processing [5] before being distributed to the market.

The job of fish farmers is to look after the fish and take care of a range of daily tasks such as feeding and maintenance. In addition to this, they regularly perform more complex operations such as lice treatments and transfer of fish to and from net cages and well boats. Fish farmers thus have to handle fish, machinery, equipment and chemicals in challenging physical environments [7]. A recent

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study shows that the aquaculture industry is statistically one of the most dangerous occupations in Norway when it comes to occupational fatalities and accidents [8]. Similarly, a study based on Canadian aquaculture concludes that workers are exposed to several potentially serious occupational hazards [9].

Official statistics indicate that the majority of reported escapes from Norwegian fish farms in the period from September 2005 to December 2009 were caused by structural equipment failures. Studies show that previous escapes have also been linked to operational related failures, external factors and escapes from land-based facilities [6]. Transportation of fish is another part of the production process linked with escape [10].

A reduction in the number of escapes in the last decade has been linked to the introduction of a Norwegian technical standard (NS9415) in 2004 which contributed to the industry investing in better and safer technology [6]. Furthermore, authorities have argued that greater awareness about escape issues as well as better work practices have contributed to the decline in escape accidents [11].

Along with the decrease in structural equipment failures, the issue of human error and human factors has gained attention when it comes to preventing fish escape. The responsibility of fish farmers is also reflected in formal regulations.

The obligation to prevent and limit escape of fish from aquaculture farm sites is described in the Regulations on fish farm operations (aquaculture operation regulations) from 2008. Regulations state that employees are expected to pay attention, conduct risk assessments and carry out systematic measures aimed at preventing escapes. All escape of fish must be reported to the authorities and to avoid future escape measures must be implemented. In regulations on internal control to fulfil the aquaculture legislation from 2005, specific demands are given regarding workers' skills and training. Furthermore, all companies are required to perform internal control to make sure regulations are being followed.

Fish escape may lead to substantial financial and legal consequences for companies and individual employees. This criminalization has been linked to a report on economic crime published in 2011 by the Økokrim, a division of the police fighting economic and environmental crime. The report designated fish escape as one of three main categories of Norwegian fisheries crime and stated that some companies fail to report and cover up escapes to avoid punishment.

Focus on fish escape impacts the reputation of the industry as a whole. Furthermore, increased media attention surrounding escapes has negatively impacted upon people who work in the industry [12].

3. Accidents and organisational aspects

This article focuses on human factors associated with fish escape. Human factors include a variety of factors that may influence people and their behaviour. For instance, a recent study from the offshore sector identifies several human factors related to organisation and personnel such as knowledge, experience, training, skills, communication, compliance with regulations, leadership, safety culture, and safety management systems [13].

In the aquaculture context human factors and human error are commonly used to describe operational-related failures. In the literature, human error has been defined as a generic term that encompasses all occasions in which a planned sequence of activities, mental or physical, fails to achieve the intended outcome [14].

Unsafe acts may be produced by organisational aspects because they influence work practice at all organisational levels [15,16]. A previous study focusing on personal safety in Norwegian aquaculture [12] applies an analytical model [17] that divides the organisational context into five dimensions. The dimensions include formal structure and organisation, technology, culture and competence, relations and networks, and interaction and work processes. Safety is thus a result of several organisational aspects. Data analysis can show how these aspects are connected and how they can be improved. Findings in this study show that management rely on fish farmers to make operational safety decisions. Furthermore, fish farm workers are interested in doing the best job possible. Consequently, the safety of the fish is sometimes prioritized before the safety of the workers themselves.

Another study of the Norwegian aquaculture industry investigates the operational setting where fish farmers make their decisions. Certain constraints and criteria that impact the decision-process are identified and discussed [5]. The most important criteria for the fish farmers is keeping the fish healthy and alive, and preventing escape of fish. It is argued that time pressure related to keeping fish safe may lead to fast decisions with unwanted consequences. On the other hand, the necessity to perform certain operations to carefully protect the fish may help prevent accidents.

A recent study of accidents in Norwegian aquaculture argues that technical, human and organisational factors should be seen as complementary and encourages accident investigations to apply different perspectives to provide knowledge about accident mechanisms and the industry itself [8]. In this article, the main focus is on the organisational aspects and how they affect individual workers. This approach explores underlying causes and risk factors leading to fish escape.

4. Material and methods

Semi-structured interviews comprised the primary method of data collection [18]. All interviews were based on an interview guide covering the following topics: critical operations, previous escape incidents, near misses, decision-making/responsibility, safety management, training, co-operation and communication, equipment, and measures taken to prevent escapes. Open-ended questions such as: "Could you explain in your own words, what happened when the fish escaped from the farm site?", "How was the work at the farm site organised at the time of the accident?" and "What do you consider to have been the cause(s) of the escape incident(s)?" were asked.

Informants were selected based on one main criterion, namely, that they were employed in companies that had reported fish escape in the period from 2009 to 2012. An official registry of escape was used to identify relevant companies. To reflect the variations in the industry, informants working in companies belonging to different geographical regions, a selection of large and small companies as well as farm sites with different technology (plastic rings and steel constructions) were asked to participate. The majority of informants that were interviewed had been present at the farm site at the time of the accident. Those who had not been present were nonetheless volunteered by their companies as informants because they knew the details of the accident well. To reflect the totality of the operations and the risk involved researchers also conducted interviews with employees of well boat companies, service vessels and harvesting plants that had been involved in escape accidents. A total of 12 informants were interviewed. Some interviews were conducted by telephone and others in person.

In addition to the interviews, data from 33 non-compliance reports were examined and included in the analysis. The reports were made available to the researchers by the companies participating in the interviews. The information given in the reports provided more data regarding escapes and near-misses that added to interview findings.

A third data source was a two-day workshop focusing on critical operations and escape prevention. The workshop gathered

21 stakeholders including representatives from trade associations, fish farmers and managers from different aquaculture companies.

All data has been analysed with the aim of identifying causes for previous escapes, and whether and in what ways organisational aspects influence escape risk. Rather than sorting findings into predetermined categories and models, the analysis presented here reflects an interpretive approach based on the empirical material.

All informants who participated in the interviews remained anonymous and all empirical data has been handled according to the principles of the Data Protection Official for Research, Norwegian Science Data Services.

5. Results

This section discusses a number of organisational aspects that have contributed to previous escape and near-incidents of fish escape from Norwegian fish farms. Furthermore, aspects that may influence the risk of fish escape in the future are described.

5.1. Technology

Technology is an integral part of the organisational context on fish farms. Technology used in aquaculture has developed and changed over the years. When informants were asked directly about the technology at the farm sites, they stated that they were happy with the status quo and that technological developments had simplified many operations. An improved focus on personal safety has, for instance, manifested itself in floating collars that allow fish farmers to walk more easily around net cages.

Despite improvements, interviews show that poor interaction between humans and technology has been a contributing factor in previous escapes. Equipment may be difficult to operate or handle and several operations are seen as critical in terms of potential escapes. For instance, one informant pointed to the use of large well boat cranes and the risk of tears in the net. The cranes put a lot of force on the net, and what happens under the water surface is difficult to see. As one informant noted, "The people who control the cranes use a joystick or crane handle and would not notice if anything got stuck".

During interviews and the workshop informants and participants were asked to describe which operations they perceived as most critical in terms of potential escape. Based on answers from all respondents, three types of operations were highlighted as particularly risky. These were: (i) handling the net and the sinker tube, (ii) conducting lice treatments, and (iii) performing operations involving boats.

The following examples illustrate potential risks involved in human-technology interaction in further detail. The sinker tube is a construction that contributes to maintaining the shape of the net cage. For certain operations, such as sorting fish into different net cages and delivering fish, the sinker tube has to be manually hoisted and lowered again in stages. Hoisting and lowering the sinker tube is regarded as a time consuming and laborious process. According to informants, all handling of the sinker tube is associated with a risk for tears and holes in the net cage, and the worry that such damage is not detected "before it's too late". Some fish farmers stated that they tried to keep the handling of the sinker tube to a minimum to reduce the risk of escape. In addition to this, companies have procedures stating that divers shall inspect the net cages following all operations where the sinker tube has been handled.

Chemical lice treatments (e.g., hydrogen peroxide) are carried out by the assistance of well boats or with a special tarpaulin. When using the tarpaulin, hoisting the net as well as installing the tarpaulin around the net cage is perceived as complicated and involves heavy lifts with crane and yardarm. Fish farmers say they do not always feel in control. Concerns focus on damage to the net cage. Sudden change in winds or currents may complicate the operation further.

Operations mentioned so far all involve the use of different vessels. Farm sites have their own work boats that allow fish farmers to access the net cages. A number of operations may also be conducted by specialised service vessels. Some companies have their own crewed service vessels that assist at several farm sites while others hire service vessels from external companies.

Well boats help with operations such as lice treatments and transportation of fish. Informants highlight use of boats as a potential escape risk. Well boats have increased in size and put substantial force on mooring lines during mooring. Consequently, there is an increased risk of structural failures. Furthermore, cranes used to handle the net cage may lead to tears. Underwater tears may be difficult to discover, thus causing fish to escape.

5.2. Physical work environment

The fact that fish farms are situated at sea means constant impact from wind, waves and currents. Cold temperatures and northern winters also influence working conditions at the fish farms. Several informants stated that bad weather and darkness made their job more difficult and that this had lead or could lead to mistakes that would not occur otherwise. With poor lighting, it is harder to see whether operations and tasks are performed properly, and examples show that night work has contributed to previous escapes as well as near accidents.

Harsh weather is also seen as a risk in itself, as it can cause damage to the fish farms that may lead to fish escape. Interviews show that, on several occasions, holes have appeared in net cages due to wear and tear, some of which have led to escape of fish. Furthermore, bad weather hinders the fish farmers' access to net cages to perform inspections which in turn increases the chance that tears are not discovered. What is perceived as bad weather depends on the individual farm site and how it is located in terms of winds and currents. Fish farmers said that daily inspections at the net cages are carried out as long as the work boats and the personnel can handle the weather. Manouvering the boat close to the net cages in bad weather was considered a risk to the safety of the workers as well as to the net cage.

If strong winds, excessively strong currents or high waves occur during operations, the work should be called off. This is, first and foremost, to ensure the safety of employees, but also to minimise the risk of damaging fish and the risk of escape. Previous experience remains crucial in decision-making processes. Fish farmers stated that, overall, they feel that they are accepted by management if they wish to discontinue due to harsh weather conditions. Nevertheless, as one fish farmer stated, "It's not fun to be the one who calls off the operations. It's difficult to balance when to say stop and when to continue".

5.3. Workload and work pressure

Long working hours and insufficient staffing are both associated with previous fish escape. One operational manager stated that sufficient staffing was crucial for all operations at fish farms. If operations are performed despite insufficient staffing, it adds to the workload of remaining staff.

Working hours at a fish farm will vary. Normally, fish farmers will work from the morning until the early evening. During labour intensive operations work is often organised in shifts and additional personnel is needed to get the job done. To ensure sufficient staffing, some companies will move personnel between farm sites while others will hire additional help. However, obtaining qualified personnel may be a challenge. This is also the case if fish farmers become ill.

A heavy work load was prominent in one informant's story of an incident involving the escape of a large number of fish following a tear in the net cage. During lice treatments workers had been working for several hours without proper rest. Due to illness they were understaffed and felt exhausted, but everyone was still determined to get the work done. However, following the operation, inspections of all net cages were not performed properly. Consequently, the tear was not discovered until later, allowing the fish to escape. Following the incident, the workers involved felt devastated.

As illustrated by the incident above, time pressure related to lice treatments is a challenge. In 2011, the Norwegian Gullestad Committee advocated a system of regional division which gave the farm sites in a given geographical area a limited period of time to perform lice treatments. As a result, informants perceive time pressure as a risk factor for both mass death and escape of fish.

Furthermore, fish farmers are part of a value chain that has to be coordinated with other actors including well boats and harvesting plants on the land side. As service and well boats commonly sail from one farm site to the next they are not necessarily able to be flexible if operations do not go as planned. Setting too ambitious goals in the planning of operations stands out as a contributing cause of fish escape.

Even though operational managers stressed that they are respected for their expertise and judgement, operational managers said they had experienced pressure from both harvesting plants and managers "higher up in the system". A fish farmer stated, "We feel pressure from the land side. It is crucial that the harvesting plants have fish at all times". Another informant stated, "It depends a lot on the individual worker, whether they demand a break if they are tired. If you feel that there are many people depending of your effort, you may stretch yourself a bit further than you would otherwise".

Several aspects thus increase the workload and work pressure for the individual worker. Consequently, this may lead to exhaustion which, when combined with time constraints, can threaten personal safety and increase the risk of fish escape.

5.4. *Training, skills and experience*

Inadequate training, lack of experience or skill may contribute to fish escape. Situational awareness and the ability to identify hazards and predict consequences of actions are crucial skills for operating workers. A statement from one fish farmer illustrates this: "Small mistakes can have very severe consequences".

Fish farmers are very aware of the responsibility they have to keep fish safe. Examples of near escapes demonstrate that the resourcefulness of fish farmers has been essential in preventing escape. For instance, one of the fish farmers interviewed recollected when they almost put up a net cage that had a hole in it. While preparing the net for installation, the hole was detected. It was most likely due to a production defect from the supplier, or damage that occurred during transportation. The fish farmer expressed relief that the hole was discovered in time.

During operations, it is important that fish farmers are aware of how to handle equipment. Experience is a crucial part of this picture. A fish farmer may be experienced in everyday tasks, but still lack experience when it comes to operations that are not performed very often. One operational manager said that he is very careful when it comes to deciding who will do certain tasks in a given operation. It is important that he knows that they have the necessary skills and experience.

Appropriate training for both new hires and experienced employees will influence their ability to handle unforeseen situations. When it comes to formal education, most companies want fish farmers with certificates of apprenticeship in aquaculture, but it is not an absolute necessity. Some companies finance certificates for their employees, because they want them to acquire theoretical knowledge.

All companies conduct on-the-job training of new fish farmers. This means that an experienced worker shows the recruit how work is conducted, and the recruit gradually takes a more active role in different tasks and operations. Full employee participation in work following induction can vary. Some are said to learn quickly while others need some time before they are comfortable with work tasks. In addition to the training given to all new employees, several companies train all employees via internal courses. Escape prevention has been a relevant topic for such courses where focus is on raising awareness, changing attitudes and contributing to safe work practices through discussion and practical exercises.

5.5. *Co-operation and communication*

Misunderstandings, poor communication or lack of communication prior to and during work has contributed to fish escape. For example, there were cases in which important messages about work were not given or messages that had been given were not followed up or not followed up correctly. The story presented in the introduction may serve as an example here. Even though it was a crucial part of the operation, the net cage had not been set up properly. Normally, work instructions were given in writing, but were not on this particular day. The fact that the net was not properly installed was never communicated to the well boat captain. Thus, the captain pumped the fish out in to the ocean, believing everything was as it should be.

During operations where several actors work together, it is crucial that there be a shared understanding of how operations should be done. The operation manager at the farm site, the captain of the well boat and service vessel as well as the management on shore all have authority to decide over their staff, and it can be useful to clarify the division of responsibilities in advance of an operation. In the interviews, this need was expressed from actors who assist the farm sites such as well boats and service vessels.

On some farm sites, start-up meetings covering all relevant operational aspects with all staff had been introduced to ensure good co-operation and communication. Informants said that a positive side effect to such meetings was that fish farmers and the boat crew got to know each other outside of a work context. These personal relationships were seen as a positive contribution to co-operation, communication and the working environment as a whole.

5.6. *Safety management: Theory versus practice*

To prevent escapes as well as ensure safety for operating workers, safety management was conducted through measures such as procedures, risk assessments and non-compliance reports. According to formal regulations, several of these activities must be documented and presented to the authorities in case of an inspection or accident. In addition to the requirements given through law, many companies have company-specific procedures that deal with safety, welfare and escape issues. The success of safety management depends on the way measures are implemented in practice, and how well they fit with the practical reality of the fish farmers.

5.6.1. *Procedures*

Non-compliance reports show that lack of procedures or lack of conformance to existing procedures has been a contributing factor to previous escapes. This is also reflected in interviews. Informants stated that violation of procedures had been the cause of escape accidents and near-misses. One operational manager firmly believed that the procedures were a challenge due to the fact that they did not exist or were not followed.

Some fish farmers argued that there may be discrepancies between procedures and actual practices because those writing operational procedures had never worked on the respective farm sites themselves, and thus had insufficient knowledge of how work was carried out. This point was also mentioned in regards to operator's manuals. Deviations from procedures are thus related to fish farmers' perceptions of the most practical solutions in a given operational context.

5.6.2. *Risk assessment*

Inadequate risk assessments have been singled out as contributing to previous escapes. Aquaculture companies perform risk assessments of specific operations as part of their internal control. The purpose of risk assessment is to identify potential hazards, assess the likelihood that such hazards will occur and the consequences they may have. This evaluation should then be used to introduce measures to reduce the probability and consequences of identified risks. The process of conducting risk assessments is also supposed to raise employees' awareness of potential risks and involve them in the work of implementing measures to minimise risks.

Informants state that local risk assessments are performed at each farm site. All employees participate and are encouraged to give input. One informant stated that even though such assessments dealt with things they already knew, it was useful for this information to be put down in writing. Even though many aquaculture companies have come a long way when it comes to risk assessment, one informant stated that there “is still room for improvement”.

5.6.3. *Non-compliance reports*

In general, companies included in this study took non-compliance reports very seriously. This is probably linked to the fact that they have all experienced escapes, and want to do what they can to prevent such accidents in the future.

Non-compliance reports are important for implementing measures such as improved equipment or new procedures and routines. Improvements cannot be made if the needs are unknown.

Over all, informants' experience was that reporting systems work well overall. However, many stated that the threshold for reporting varied considerably among employees. The following statement illustrates this: “Some report a knot that has come undone, others do not report unless there is a hole in the net cage”. Workers note that things that are easily fixed are less frequently reported than those that require further action. Interviews also showed that other more informal mechanisms are important. Discussions amongst employees in everyday life had, for instance, led to improvements.

6. Discussion

The results presented in this article show that escape accidents in Norwegian aquaculture commonly explained by the term “human error” can be linked to several contributing factors. Interaction with technology, physical work environment, workload, work pressure, training, skill, experience, co-operation, communication, and safety management are all aspects that may influence the risk of escape of fish from fish farms.

Even though the focus here has been on escape accidents, findings presented in this article resemble those of a previous study looking at organisational context and personal safety [12,17], where it was argued that accidents may be prevented by improved technology and practice as well as through considering the organisation of work, communication, skills and experience, workers' sense of responsibility, learning, and safety perception.

Another study notes that workers at fish farms feel that higher profit is prioritised before personnel safety [12]. Economic considerations relating to production costs may also underlie several aspects presented in this article. For instance, investing in technology, ensuring sufficient staffing, conducting training and hiring well boats and service vessels for an adequate amount of time all come at a cost. This in turn influences the work load and work pressures for fish farm workers.

The term “fatigue” refers to both physical and mental exhaustion and originated in medical literature, where it was first associated with the harmful effects of overexertion [19]. Human fatigue is difficult to measure, but factors found in the occupation of seafaring, such as long working hours, disturbances of sleep and sleep rhythm, night work and harsh working conditions and ship motions are commonly associated with fatigue [20]. A previous study focusing on shift work aboard offshore vessels demonstrated that a direct cause of fatigue is an accumulated sleep deficit over time [21]. Another study concludes that long working hours with few breaks at moving work platforms also affect cognitive and physical performance [22]. It is thus likely that long working hours and little sleep in addition to a high work load and work pressure during labour-intensive operations will likely influence fish farmers' performance.

Looking at escape accidents and risk, the role of the operations manager and the fish farmers is particularly important when it comes to influencing organisational aspects. Each farm site is managed by an operations manager who makes the most of everyday decisions. Operations managers have to make sure that staffing is adequate, that no-one works illegal overtime, that operations are well planned, that communication with on-shore management, service vessels and well boats is ensured and so forth. They are also responsible for their own as well as the fish farmers' actions if fish escape from the farm site. Thus, decisions made at the farm sites can be crucial for the outcome of a given situation.

In sum, the role of the operational manager entails great responsibility, and can result in great stress. Results presented in this article show that operational managers and fish farmers are very conscientious and do everything possible to prevent fish escape. No-one wants to make mistakes or errors. In fact, they are afraid to make mistakes, because the consequences for themselves and the company are so severe. Escape of fish may lead to economic loss, economic penalties and damage the reputation of the company. Because escape is considered one of the worst possible scenarios, fish farmers keep a major focus on the maintenance and supervision of net cages. As shown in a previous studies, fish farmers may even put the safety of the fish before their own safety [5,12].

7. Conclusions

Workers' performance is influenced by organisational aspects, and this needs to be taken into consideration in the industry's efforts to prevent fish escape. Analysis of previous fish escapes shows that the term “human error” may hide the complexity of accident causality. Furthermore, this terminology may be perceived as incriminating by the fish farmers who are conscientious and always anxious to prevent escape.

It seems that escape incidents in the past have served as a warning for the industry that has led to the implementation of new measures to prevent escape in the future. However, as this article suggests, it is important that these efforts continue, as there is still room for improvement in several areas.

First, there is a need for increased awareness on the consequences organisational aspects have on individuals. Second, there is a need for user-friendly technology that is robust and weather-resistant. Safety for both fish and people can be improved by simplifying operations and improving equipment. Finally, fish farmers disregarding personal safety due to fear of escape is a negative consequence of the responsibility they are given. It is important that fish farmers truly feel that they can put personal safety first.

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Article 3

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Organisational safety indicators in aquaculture—a preliminary study

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ABSTRACT: The aquaculture industry has since the 70's grown to become one of the most important industries in Norway. A safety challenge for the Norwegian fish farming companies is escape of salmon. During the last decade, the main cause to escapes has changed from structural failures to "human errors". The paper addresses the need for improving safety in fish farming operations by implementing systematic means for risk management. The objective of this preliminary study has been to evaluate whether the Operational Safety Condition (OSC) method provides a feasible tool for identifying and understanding organisational factors and conditions that influence safety levels at the fish farms. The basis for the study is escape of fish. The results demonstrates that OSC seems to be a promising tool for audits of the organisational safety conditions in aquaculture companies.

1 INTRODUCTION

1.1 *Background*

The aquaculture industry has during the last 40 years grown to become one of the most important industries in Norway, and Norway is now the dominant producer and exporter of Atlantic Salmon worldwide. The industry has been in constant development and is now aiming to reach a production of 5 million tons of farmed fish per year by 2050 (Olafsen et al. 2012), up from around 1.3 million tons in 2013. Due to the increasing need for more space and better production environments (Holmer 2010), there has been a gradual move towards also using more exposed coastal areas. Farming in exposed areas poses unique challenges to operations, structures and equipment, due to extreme weather, wave and current conditions, and sheer remoteness (Bjelland et al. 2015). Technology is gradually developed to meet these challenges; so far mainly by upscaling boats, fish farms and net cages.

Exposed farm locations could be ideal for production and simultaneously reduce key environmental effects, as well as the negative ecological consequences of sea lice (Costello 2009) and escapees (Jensen et al. 2010). Fish farmers, who have gradually started to utilize more exposed locations, report considerable difficulties in maintaining reliable production (Sandberg et al. 2012). Weather conditions are already causing downtime at several sites, especially during the winter months, and this is expected to increase due to climate changes. This makes the overall management of maintenance and daily operation unpredictable, and challenges the safety at the fish farms (Holen et al. 2013). Lack of repairs and daily inspections of fish cages may increase the risk for fish escapes. Maintenance and safety management strategies have to be changed in line with the harsher operating conditions (Utne et al. 2015).

Escape of fish is a great challenge for the Norwegian fish farming companies. A fish escape incident may consist of from one to several tens of thousands of fish being accidently released from a net cage. The fish farmers are decreed to report every escape, also upon suspicion. The number and average size of the escaped fish shall be reported to the Directorate of Fisheries, which will investigate the incident. The company in charge of the escape are obliged to reduce the environmental damage by catching the escaped fish with nets. To avoid new escapees, they must document implementation of relevant actions. The loss of fish implies a financial loss, but perhaps even more damaging is that such accidents severely harm the reputation of the industry. Escaped fish might disrupt gene pools of wild salmon (Bourret et al. 2011), thus affecting the environment. Furthermore, escape of farmed fish is criminalised and the company and/or the employees might be prosecuted and fined if the investigation reveals misactions or noncompliance with mandatory safety procedures. This may lead to severe personal strain (Thorvaldsen et al. 2015). The workers are likely to take action to prevent escapees even though this might expose themselves to hazards (Størkersen 2012).

Current research shows that the accident causality often is complex and with several contributing factors. Such factors are, for example, the harsh work environment that the operators have to deal with, demanding work operations, variations in worker experience and skills, poorly implemented safety management, and suboptimal functionality of technology (Thorvaldsen et al. 2015). Previous interviews with operators and managers at fish farms also show that most of the operations regarded to be critical for the escape of fish, also implies a considerable occupational safety risk. Thus, means for reducing the risk of fish escape may also improve the safety for the workers.

1.2 *Objective and scope of paper*

This paper addresses the need for improving safety in fish farming operations by implementing systematic means for risk management. Risk management deals with identifying, analysing, assessing and controlling occupational risk and major accident risks, as a basis for developing preventive measures (ISO 31000:2009). The management system should enable good safety practice in all parts of the organisation, and ideally, it should have a built-in resilience against human errors. Thus, it is crucial to understand how organisational factors and conditions influence safety levels. Furthermore, internal audits should be performed at intervals in order to check the safety levels in the fish farming companies' daily routines. To make the audits efficient, they need to focus on the critical safety factors relevant for the operations at the fish farms. The objective for this paper is to evaluate whether the Operational Safety Condition (OSC) method provides a feasible tool for identifying and understanding organisational factors and conditions that influence safety levels at the fish farms. The basis for the study is escape of fish.

2 REGULATIONS ON SAFETY MANAGEMENT IN AQUACULTURE INDUSTRY

All Norwegian enterprises are obliged to implement some kind of performance management systems, to control quality, working health, safety and/or possible damage to the environment. These could be integrated in one management system, but typically current practice is that maintenance schedules and records are often found in different systems. Software-based management systems are implemented because it is a rational way of ensuring sound and effective daily operations, and because governmental regulations make them mandatory.

Audits are an important tool in the implementation of "living" management systems. Safety audits are a systematic and planned verification of the safety performance against external and internal requirements. They can be conducted as internal audits or by a third party.

The use of audits within safety management is derived from quality management theories (Kongsvik 2013). International standards for quality management, e.g., ISO 9001 (International Standard Organisation 2015), have been established and are widely used as the basis for certifying enterprises. Accredited certification by an independent third party is a confirmation that the company performs according to the requirements in the standard, and has become a quality stamp that several companies obtain.

2.1 *Internal control of health, safety and work environment (HSE)*

Since 1992, it has been decreed by law that all enterprises under the authority of the Norwegian Labour Inspectorate Agency (LIA) shall work systematically with, and continuously improve the health, safety and environment (HSE) procedures. This implies implementing and maintaining a safety management system at the minimum standard, as described in the internal control regulation. The present version of the "Regulation on systematic health, safety and environment work in enterprises (Internal control regulation)" came into force in 1997, and was last updated in 2014 (Norwegian Ministry of Labour and Social Affairs 1996). The Working Environment Act, which applies for all land based industries as well as the aquaculture sector in Norway, sanctions this regulation (Norwegian Ministry of Labour and Social Affairs 2005).

The internal control regulation's purpose is to ensure that the safety policy and management systems comply with the HSE legislation, and that the internal procedures, laws and regulations are easily available to employees. The companies must document descriptions of HSE functions and responsibilities in the organisation, as well as risk assessments and plans for implementing risk-reducing actions. The employees shall be active contributors and get the sufficient training to be able to do so. The company are supposed to continuously follow up and systematically revise or update the safety management system, and the management must conduct internal audits at set intervals to check the performance of it. LIA will check the documentation of this work during inspections, which will be valuable documentation when investigating accidents. The environmental part is controlled separately by the county administration.

2.2 *The aquaculture legislation and internal control*

The aquaculture industry's obligation to prevent escape of fish, and to report either suspected or known escapes, is stated in the "Regulation on the operation of aquaculture production sites" (Norwegian Ministry of Trade and Fisheries 2008), statutory in the Aquaculture Act (Norwegian Ministry of Trade and Fisheries 2005). Certain parts of this regulation deals with ethical and sound farming of fish and are linked to clauses in the Food Act and the Animal Welfare Act. The Norwegian Food Safety Authority controls these parts.

According to the aquaculture legislation, the companies are obliged to show risk awareness, conduct risk assessments and implement measures to mitigate the identified risks. Furthermore, actions have to be taken if an escape incident happens, by trying to catch escaped fish. There are also requirements on training and competence of the fish farm operators.

Formal requirements on internal control of the aquaculture production are described in the "Regulation on internal control to comply with aquaculture legislation" (Norwegian Ministry of Trade and Fisheries 2004). The system requirements are almost equal to those for the HSE internal control, thus making company management and workers responsible for the safety performance during daily operations. The Norwegian Directorate of Fisheries is the regulatory authority for these requirements, as well as the technical regulations described in the next section.

2.3 *Technical regulations*

The "Regulation on technical requirements to floating aquaculture installations" (Norwegian Ministry of Trade and Fisheries 2011) was introduced to ensure that the standard of fish cages and installations comply with the technical requirements in the Norwegian standard NS 9415 (Standard Norway 2009) for aquaculture production sites. This standard was developed in order to mitigate the increasing numbers of escaped fish due to structural breakdowns or technological failures in the first years of this millennium, and soon proved a success (Jensen et al. 2010). However, escape incidents due to errors, lack of safety barriers or other operational causes, still is a challenge for the fish farming industry.

3 METHODS FOR ASSESSING AND MONITORING SAFETY IN AQUACULTURE

Today, there are few parameters used to systematically measure the safety performance level in Norwegian aquaculture. First, the number of escaped, and suspected escaped, farmed fish is followed closely. The industry has established good routines for reporting in accordance with the authorities' regulations (Norwegian Ministry of Trade and Fisheries 2008), which state that one should report when it is assumed or known that one or more fish have escaped. Furthermore, lice counts are done on a regular basis as defined by the authorities, and levels above 0.5 louse per fish initiate delousing. The delousing operation is identified as critical when it comes to risk for escapes and occupational risk (Thorvaldsen et al. 2015), and increased frequency of delousing should alert the companies to take extra precautions. Serious occupational accidents are reported to the Norwegian Labour Inspectorate Agency (Holen et al, in prep) and the investigations may result in suggestions for preventive actions. Company-internal measures, for example, number of reported nonconformities or near misses, is also likely to correlate with the operators' alertness at work. Still, it can be questioned whether any of these numbers are efficient – or sufficient – indicators for the organisational safety performance in the Norwegian fish farming industry, either nationally or at company level.

The Operational Safety Condition (OSC) method was developed to measure the effect of mitigating actions on operational safety levels over time (Skogdalen et al. 2011). Hence, it may be used for developing safety indicators. Safety indicators are observable measures providing information about safety or the safety level, in an organisation, at a workplace, or during an operation (Kongsvik 2013). Such parameters may be useful in order to develop safety barriers, prioritize and evaluate the effectiveness of preventive measures, or simply satisfy authority requirements with respect to safety management. The overall aim of the OSC development was to reduce the risk of major accidents at offshore installations (Kongsvik et al. 2010).

OSC was introduced as a supplement for assessments of technical conditions on a production facility, i.e., the Technical Condition Safety method (TTS) developed for the oil and gas industry (Ingvarson & Strom 2009). OSC has been developed based on the same basic principles as TTS, which reviews safety critical barriers in maintenance, inspection and design. TTS checks a number of performance indicators related to safety functions that are verified against defined performance standards. A detailed checklist is used to conduct the assessment, and the performance levels are rated according to grades A-F (Skogdalen et al. 2011). As the aquaculture technology advances, the need will increase for systems that monitor the technical safety as well. OSC and TTS supplement each other, and a combination could rationalise the audit processes since several of the underlying safety and risk factors will overlap.

OSC focuses on the "soft" barriers in safety work: Humans and the organisation. The motivation behind OSC was to reduce the risk of major hazards in the oil and gas sector by introducing a method for proactive organisational safety verification and improvement. The core of the method is to compare operational practice against safety requirements (Kongsvik et al. 2010, Skogdalen et al. 2011, Kongsvik 2013). In the Norwegian oil and gas sector, human and organisational factors have to be included in the risk assessments to comply with the health, work environment and safety legislation (Skogdalen & Vinnem 2011). This also applies to the aquaculture industry since the Work Environment Act is regulatory for these workplaces, as well (Norwegian Ministry of Labour and Social Affairs 2005).

OSC is a qualitative method. Interviews with personnel, observations of work procedures, investigations of documents and questionnaires are input to the verification of operational practice versus requirements. The method involves the operators to a great extent and makes them co-owners of the problem, process and necessary changes. The method should be used and managed by company internal HSE personnel. The results should provide information on how organisational factors function and interact with

Table 1. Steps of OSC method (Kongsvik et al. 2010, Kongsvik 2013).

1. Identify causes for accidents.
2. Which work operations are they connected to?
3. Which organizational conditions/factors are of importance for these tasks?
4. Which internal and external requirements are relevant for each factor?
5. Define checkpoints for each requirement (could be several).
6. Conduct the audit: Evaluate the accordance between the organizational factors and relevant requirements.
   a. Background information: accident statistics, reported accidents, incidents, nonconformities.
   b. Surveys and personal interviews.
   c. Overall analysis, evaluation and reporting. Interpret and describe the organisational safety condition.
   d. Workshop with participants from all levels of the organisation. Generate knowledge and identify measures based on findings in steps above.

respect to safety. The steps of OSC are listed in Table 1. These are further discussed in the next section.

4 THE OPERATIONAL SAFETY CONDITION (OSC) ADAPTED TO AQUACULTURE

In this section, the results of the preliminary study are summarised. The work has followed the steps listed in Table 1.

4.1 *Step 1 – Identify causes to accidents*

The development of the OSC method is based on identified risk influencing factors with high significance for major hazards (Kongsvik 2013). In this paper escape of farmed fish is defined as the undesired incident. The first step in adapting OSC to aquaculture, according to Table 1, is to identify known accident causes from available information sources, literature and supplementary interviews with personnel. For the case of fish escape, relevant background information about causal factors can be found in escape statistics and reports from the Norwegian Directorate of Fisheries (2016). Furthermore, a number of research reports have been used to identify direct and contributing causes for escape of fish, both technical and structural causalities (Jensen et al. 2010), focus on complex operations (Sandberg et al. 2012), organisational aspects (Fenstad et al. 2009, Størkersen 2012), and human factors and organisational aspects (Thorvaldsen et al. 2015). Structured interviews could also be conducted with workers at fish farms to add to this material when necessary. Table 2 summarises categories of causes and examples of contributing factors to accidents with escape of fish.

Table 2. Some identified causes to escape of fish in Norwegian aquaculture.

Category	Example of cause and contributing factors
Structural/ technological failure	Barrier not functioning – net cage missing or whole in net due to wear and tear, material fatigue or propel caught in net
	Crane operations – no control of forces
Human-technology interaction	Suboptimal design, allows errors
	Insufficient user instructions and/or handbook
Operational	Internal control not implemented
	Understaffing and long working hours – heavy workloads, fatigue
	Insufficient training of operators
	Operation planning lacks clarification of responsibilities and abortion criteria
	Risk assessments are not conducted
	Communication routines not clarified
	Poorly described procedures
External conditions	Time pressure
	Economic pressure
	Bad weather, heavy winds, waves and strong currents
	Darkness
	Insufficient resources, manning, equipment

4.2 *Step 2 – Map work operations*

Previous studies have identified aquaculture operations with particularly high risk for fish escape (Jensen et al. 2010, Sandberg et al. 2012, Thorvaldsen et al. 2015). The most important are: Crane operations, delousing, well boat operations, daily work and maintenance, inspections of mooring lines and net cage, net cage replacement, transfer of fish and feed deliveries.

4.3 *Step 3 – Organisational factors of importance*

The work operations and tasks connected to these causes from step 2 are mapped with organisational conditions that have an impact on the performance or outcome of each task. A description of how each organisational condition affects the work tasks must then be provided, together with a classification of their influence (high, medium, minor). Based on this, a list of organisational factors with high influence on the operational practice is developed. Kongsvik et al. (2010) have identified seven overall factors based on a literature study:

1. Work practice
2. Competence
3. Procedures and documentation
4. Communication
5. Workload and physical environment
6. Management
7. Change management

Regarding the organisational conditions of highest relevance for the work tasks, we approached the task by evaluating the seven organisational factors listed by Kongsvik et al. (2010) against the operational

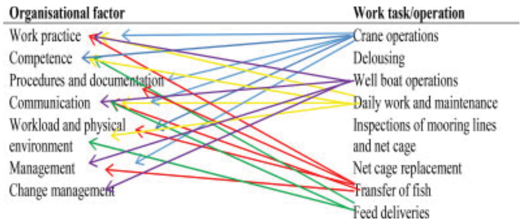

Figure 1. Dependencies between organisational factors (Kongsvik et al. 2010) and aquaculture operations with a high risk of fish escape.

challenges identified in aquaculture operations hazardous with respect to fish escape (step 2, section 4.2). Figure 1 illustrates the preliminary results, which show that the organisational factors identified for the oil and gas sector applies to the fish farm operations. In Figure 1, arrows are drawn to show examples of dependencies between operational factors (right) and work operations (right).

4.4 *Step 4 – Internal and external requirements*

Step 4 is to establish safety performance, internal and external requirements relevant for each condition mapped. These can be found in company internal policy documents and procedures, or in authority regulations. An initial assessment has been performed for the seven organisational conditions with respect to operations with a high risk of escape. In Table 3, we have listed examples of relevant requirements and suggested checkpoints (step 5, next section), as well as suggested sources for identification of requirements. The requirements should be found both in regulatory (mandatory) regulations, as well as company internal regulations. Due to limitations in space, only a few of the factors are shown in Table 3. For example, related to work practice, all employees should be familiar with the operational procedure and also acknowledge that they know it by placing their signature on it. Further examples are shown in Table 3.

4.5 *Step 5 – Define checkpoints*

Finally, step 5 in the development process is to identify checkpoints in order to assess whether the organisational condition complies with the requirements. Some of the checkpoints can be developed into safety indicators, or be included in safe job-analyses to be performed prior to operations with significant risk for accidents. The present Table 3 (next page) is not comprehensive and should be developed further to establish a complete basis for safety audits in aquaculture companies.

4.6 *Step 6 – Conduct the audit*

The resulting list of organisational factors, requirements and checkpoints then forms the basis for interview guides and/or questionnaires to be used in the safety audit. The audit should reveal both weaknesses and strengths of the organisation, and include personnel at all levels. For fish farming companies this should involve representatives from top management, HSE managers and personnel, fish farm operators and operational managers.

5 DISCUSSION

Preventing fish escapes have been the main motivation for improving and implementing performance requirements for aquaculture technology and structures. The effect of these measures is mainly evaluated in terms of reduction in escapes, both regarding number of incidents and number of fish. The escape reports the last decade show that in relation to the increase in total production of farmed fish, the number of escapes are considerably reduced. Nevertheless, escape of farmed salmon is still a major hazard in the aquaculture industry due to serious consequences for the ecosystem (wild salmon), industry reputation, and financial losses.

Methods have been developed in other industries in order to be able to measure risk development at workplaces. The Petroleum Safety Authority Norway (PSA) established in 1999 the RNNP project to develop a method for monitoring the risk levels in the petroleum activity on the Norwegian continental shelf. The goal is to control the major hazard risks for workers on offshore installations (Vinnem et al. 2006), and RNNP contributes to a shared understanding of risk development between industry companies, unions and authorities (PSA 2016). Since the pilot study in 2001 annual updates have been performed. It consists of both quantitative and qualitative methods that are complementary to each other. RNNP is now established as an important management tool for all parties in the oil and gas sector. Similar tools could thus be relevant also for the aquaculture sector.

A recent study on the escape of fish and influence of organisational aspects shows that organisational factors are significant contributors to the escape accidents (Thorvaldsen et al. 2015). When the safety barrier is lacking or not functioning because of holes in the net, a direct contributing factor is that the net cage handling has been incorrect. The root causes may be lack of sufficient training, competence or heavy workloads. Other contributing factors have found to be lack of communication or (non-reported) nonconformities in the operational procedures. A recommended way forward would therefore be to develop tools to ensure that the state of the organisational conditions and factors within the fish farming companies is checked regularly.

The development of OSC was based on a need to systematically and qualitatively measure the operational safety performance at process plants or offshore installations, as a supplement to technical safety as a means to identify where improvements are required. The aim of the method is to set a performance standard for the organisational risk controlling systems and evaluate how well they function as operational safety

Table 3. Examples of relevant requirements and checkpoints for the two organisational conditions "work practice" and "competence" in aquaculture operations.

Organisational factor
- Source to identify requirements
  - Requirements
    - ✓ Checkpoints

Work practice
- Internal quality and safety management system
- Policy documents
- Interviews
- Certifications e.g. Aquaculture Stewardship Council (ASC), ISO 9001, OSHAS 18001
- Regulatory requirements
  - All employees should know the procedures and sign it.
  - All personnel shall be trained according to the requirements in the management system.
  - Internal control Aquaculture: hazard identification, risk assessments and develop action plans, preventive measures
    - ✓ Are all operations described in the management system?
    - ✓ Are risk assessments and evaluations performed for all tasks?
    - ✓ Are the procedures for use of personal protective equipment described?

Competence
- IK Aquaculture
- Internal quality and safety management system
- Work procedures, skill requirements
- Certifications e.g.Aquaculture Stewardship Council (ASC), ISO 9001, OSHAS 18001
  - The personnel know the purpose and content of the internal control procedures.
    - ✓ Does the company have a procedure which describes the competence and skills required?
    - ✓ Are the competence requirements clearly defined in the management system?
    - ✓ Are safety training conducted for operators?
    - ✓ Is the education and training of the employees documented?

barriers (Kongsvik et al, 2010). OSC is thus likely to be applicable to other production industries where human and organisational factors have significant impact on the safety levels in the operations, as in the fish farming industry.

There is also a need for establishing effective safety indicators that give a prewarning if the risk for fish escape. Today, the safety indicators are lagging in the form of number of escaped fish. The information gathered using the OSC method could probably be used to develop organisational safety indicators that address specific safety challenges in companies, regions or locally at a fish farm. A good approach could be to start with the regulatory requirements for internal control that are mandatory and known to the company management.

The performance of safety management systems in the aquaculture industry shall be audited regularly as a part of the internal control. Regulatory authorities conduct inspections at intervals, and they have the policy to do so-called risk based audits, i.e., they will check the parts of the management systems that is relevant for the known major risks in the industry. At the time being, this includes procedures and operations that are associated with risk of fish escape and lice treatments. The internal control often reflects this in practice, as the companies aim to be up to standard during the audits. Furthermore, easily available parameters are most likely to be inspected, for example, written procedures, nonconformity reports or equipment maintenance. The correlation between a net cage which is not properly installed and organisational factors is not obvious, and such an error is a result of the interaction between humans, technology and organisational factors. This supports the use of methods like the OSC that takes a more holistic approach.

The seven organisational conditions identified to reduce the risk for major hazards in the oil and gas industry (Kongsvik et al, 2010), seems to be relevant also for the aquaculture industry. OSC goes into the depth of the problem and provides an assessment of the organisation as an entity, and covers different authorities' regulations. This allows an overall approach which is useful for the company's quality management activities. The information gathered during the audit forms the basis for development of necessary operational changes. The improvements are discussed jointly by all parts of the organisation, and this kind of dialogue between operators and top managers is catalysed using OSC. The process is resource-demanding and requires considerable man-hours from process leaders and employees. Ownership and understanding among the operators dealing with the challenges daily ensure that the most effective preventive measures to be developed. It is likely, however, that the fish farms along the Norwegian coast are quite similar with respect to organisational conditions, and OSC could therefore be developed as a joint effort across the key players in the industry. Parts of the OSC can be repeated at intervals and thus provide key information on safety performance useful for the company's management, but also for the regulatory authorities. The results could be used to establish safety indicators on safety performance at industry level, similar to the oil and gas sector through the RNNP project. Minor adaptations in the safety audit checklists could subsequently be conducted within each company. This would represent a significant contribution to improving the safety levels in the fish farming industry.

6 CONCLUSIONS

This paper presents a knowledge basis for adapting the Operational Safety Condition (OSC) method to the aquaculture industry. During the last 10 years the industry has accomplished a great reduction in the number of escapes due to escape incidents caused by technical failures in constructions and equipment. The next step is to improve the organisations and management systems at the fish farms in order to reduce the organisational risk factors in the aquaculture industry and avoid "human errors".

This paper presents a knowledge basis for adapting the qualitative method called Operational Safety Condition (OSC) to the aquaculture industry. Part of the method is to develop a detailed checklist, tailored according to the requirements identified for each organisational safety condition. The pre-study demonstrates that OSC seems to be a promising tool for audits of the organisational safety conditions in aquaculture companies.

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Risk assessments in the Norwegian aquaculture industry: Status and improved practice

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ABSTRACT

The Norwegian aquaculture industry has the potential to become the country's leading ocean industry in the future. More than 99% of the produced biomass is Atlantic salmon and trout. Norwegian fish farming is characterised by operations that are susceptible to changing weather, wind and currents, and face challenges in terms of safety for fish, personnel, environment and material assets. Previous research and accident analyses reveal an incomplete knowledge of risk factors during aquaculture operations. In order to raise standards of safety in the workplace, operators need to be aware of the challenges to safety in their work environment. The objective of this paper is to describe and discuss the current status of the implementation of risk assessments in the Norwegian aquaculture industry, according to Norwegian legislation and compared with recommended requirements in the Norwegian standard for risk assessments (NS 5814). This standard largely follows ISO 31000 for risk management. We also propose, test and evaluate an improved approach to risk assessment that will ensure stronger operator involvement. Our findings demonstrate that there are several gaps between the current practice and the standard. At the present time, operator involvement is not sufficient according to the regulatory requirements of internal control. Although the approach improves critical steps in the risk assessment procedure, it remains to be implemented in the fish farming industry.

1. Introduction

The Norwegian aquaculture industry has the potential to become the country's leading ocean industry in the future (Norwegian Ministry of Trade Industry and Fisheries, 2017). This ambition will require new biomass production sites to be established, and major environmental and technological challenges still have to be resolved (Bjelland et al., 2015). The aquaculture industry has become a driving force for the development of new technology, concepts and management strategies that meet the requirements for sustainable production in harsh environments. An important task in this development is to evaluate how safety risks in aquaculture can be reduced by integrating risk assessments in the engineering phase, as well as implementing new strategies for fish farm operations.

The fish farming industry is characterised by operations that are susceptible to changing weather, wind and currents, all of which affect the availability, safety and integrity of fish farms. Fish farming is thus a challenge to technology manufacturers, fish welfare and occupational safety. In Norway, being a fish farmer is the second most dangerous profession after capture fisheries in terms of rates of occupational injuries (Aasjord and Geving, 2009; Holen et al., 2018a). Between 1994 and 2014, 21 fatalities were registered, and the rate per 10,000 person-years worked ranged from 0 to 10.8 (Holen et al., 2018b), with an average fatality rate of 2.9. Since 2005, there have been nine fatalities during maintenance or other marine operations related to aquaculture production (SINTEF Ocean, 2018). Operations involving cranes or winches are the major contributors to these incidents (Holen et al., 2018b), many of which are performed as part of work-intensive delousing procedures. Lice and infections pose a hazard to fish welfare and health, as the treatment procedures cause stress and involve rough handling of the fish. Violations of the Animal Welfare Act will be investigated and may lead to fines (Norwegian Ministry of Agriculture and Food, 2009). Systematic regimes to monitor fish welfare and conduct delousing are mandatory (Norwegian Ministry of Trade Industry and Fisheries, 2016b; Food Safety Authority Norway, 2017).

Besides threatening fish welfare delousing also raises the risk for occupational injuries and for escape of fish. After years of growing numbers of escaped fish, action was taken after 2000 to reduce the number of incidents caused by structural breakdowns and technological failures (Jensen et al., 2010). Operational errors and structural

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deficiencies due to insufficient or missing safety barriers are now the most frequent causes of escapes (Directorate of Fisheries, 2017b). An analysis of farmed salmon and trout escapes between 2010 and 2016 has shown that holes in the net are the major direct cause, and these are mostly due to bad handling or conflicting integrity with the bottom weight system of the fish cage (Føre and Thorvaldsen, 2017).

Escapes are not only a threat to the environment, but also contribute to the negative reputation of the industry (Olsen and Osmundsen, 2017). Fish farmers report that personal safety may be set aside in order to prevent a- fish escape accident (Størkersen, 2012; Thorvaldsen et al., 2015). A study by Holmen and Thorvaldsen (2015) showed that the aquaculture industry lies behind comparable industries in implementing systematic risk management. Previous research and accident analyses reveal a considerable lack of understanding of the risks involved in marine operations in aquaculture (Holmen et al., 2017b, c; Holen et al., 2018a, b; Jensen et al., 2010; Thorvaldsen et al., 2015; Føre and Thorvaldsen, 2017). In this context, fish farmers' knowledge of operational hazards, experience and skills are important organisational safety barriers. Risk assessments and personnel training may therefore be important safety factors. This calls for a more comprehensive approach to risk management in the fish farming industry. A recent study recommends that five dimensions of risks need to be assessed in a fish farm operation (Yang et al., 2018). These are risks to personnel, material assets, fish welfare, the environment and food safety.

Risk assessment is a core activity of risk management and consists of identifying hazards, analysing and evaluating risks, and among outcomes are action plans for risk treatment during the design and operational phases of a production unit (ISO, 2018; Rausand, 2011). A starting point for the fish farming industry could be to implement improved strategies for thorough assessments of operational risks as a basis for developing effective preventive measures, as well as increasing workers' awareness of the risks inherent in daily work. Recognition of occupational hazards is fundamental in order to implement efficient safety measures in aquaculture (Moreau and Neis, 2009; Myers and Durborow, 2012). In Norway, it is a regulatory requirement that operating personnel are to be involved in the risk assessment process, in order to ensure that relevant workplace hazards are identified and understood by those actually performing the work (Norwegian Ministry of Labour and Social Affairs, 1996).

The objectives of the paper are to present the status of risk assessments in the Norwegian aquaculture industry, and thereafter to discuss how the implementation of risk assessment might be improved in order to fulfil the intention of the standard and of the regulations. Part of the study has been published previously in Holmen et al. (2017c), which is a brief presentation of the regulatory requirements for risk assessments in aquaculture operations, a summary of current practices and an recommended improved approach to hazard identification and risk analysis, in the Norwegian context. The present paper extends both the data material and the scope of the study by comparing current risk assessment practices step by step with the risk assessment process recommended by the standard NS 5814 (Standard Norway, 2008), which largely follows the international standard for risk management, ISO 31000 (ISO, 2018).

The paper is structured as follows: Section 1 introduces the aquaculture industry context and its safety challenges, as a background for the objectives of this paper. Section 2 presents requirements for risk assessments in Norwegian aquaculture regulations and standards related to risk assessments. Section 3 presents the results from a systematic analysis of the current practice for risk assessments and is followed up by a suggestion as to how the practices could be improved (Section 4). The results are discussed in Section 5, and the conclusions in Section 6.

2. Regulations and standards for risk assessments in Norwegian aquaculture

2.1. The Norwegian fish farming industry

The Norwegian finfish aquaculture industry comprises all sizes of companies from large global enterprises to family-owned fish farms in small communities. There is also a growing number of manufacturers and providers of equipment, components, vessels and services to the aquaculture industry. Norway is the world's second largest exporter of fish after China, but the largest producer of finfish in marine and coastal environments (FAO, 2016). More than 99 per cent of the Norwegian total produced biomass is farmed Atlantic salmon and trout (Directorate of Fisheries, 2017a), which is the focus of this paper.

There are normally six to 12 circular plastic collar net cages in one fish farm (Jensen et al., 2010; Holen et al., 2018a). The number of cages differs according to the site and production license. Each cycle of fish is grown out in seawater for 18 months before it is slaughtered. The operations manager is responsible for both production and personnel safety. Each fish farm employs about three to six workers (in this paper also referred to as fish farmers or operators) who are responsible for daily inspections, feeding and maintenance. The feeding barge, which is the "operations centre" of the farm, contains rooms for equipment and feed storage, the feeding system, as well as offices, meeting rooms and accommodation for the workers.

Designated work vessels, from 8 to 15 m length overall (l.o.a.) and equipped with capstans and/or a crane, are used for inspection and maintenance of the fish cages. The daily inspections are performed in accordance with official regulations on aquaculture operations (Norwegian Ministry of Trade Industry and Fisheries, 2008), and are intended to ensure that the net cages are in order and to assess fish welfare. The operators perform such tasks as maintenance, removal of dead fish from the net cages and monitoring the amount of salmon lice on a sample of fish every week. Specialised service vessels and crews, either the company's own or belonging to subcontractors, are chartered for heavier operations such as mooring and delousing.

A wide range of equipment for monitoring and caring for the fish is mounted inside the net cage (Holmen et al., 2017a). Examples include hideouts (shelters) for wrasse (small size "cleaning fish" which feed on salmon lice), air tubes, cameras, gear for removal of dead fish and much more. The equipment may represent hazards to the fish or the net and has to be handled carefully if it has to be removed before an operation can start. During operations, extra devices and equipment may be needed; e.g. remotely operated vehicles (ROV), tubes for pumping fish or a remotely operated cleaning system positioned by a crane. All this extra gear adds complexity to the operations. Furthermore, aquaculture operations are not standardized, neither between companies nor between fish farms in different regions, and different equipment may be used, depending on what is available (Holmen et al., 2017a). All of these factors have consequences for the risk assessments, because hazards must be identified for each specific operation.

2.2. Regulations

The administration of the Norwegian aquaculture industry is fragmented as regards legislation and the regulatory authorities involved. Coastal area management, allocation of fish farm licences, planning and establishment of sites, inspection of fish welfare and health, food production and environmental protection are allocated to six different ministries and regulatory authorities. In certain areas the audits are delegated to regional or local community offices, which in turn increases the potential for differences arising in how cases are dealt with (Robertsen et al., 2016). The requirements regarding risk management in production are also fragmented (Holmen et al., 2017c).

Performing and documenting risk assessments for all aquaculture operations is mandatory, as are activities related to breeding and

Table 1
Norwegian regulations, statutory acts and authorities sanctioning risk assessments in aquaculture.

Topic	Regulation Statutory Act(s)	Norwegian regulatory authority	Focus of risk assessments	Purpose
Fish welfare and health Food safety	Regulation on the operation of aquaculture production sites (Norwegian Ministry of Trade Industry and Fisheries, 2008) Regulation on internal control to comply with the aquaculture legislation (Norwegian Ministry of Trade Industry and Fisheries, 2004) Food Act (Norwegian Ministry of Health and Care Services, 2003) Animal Welfare Act (Norwegian Ministry of Agriculture and Food, 2009)	Food Safety Authority	Health control parameters and water quality. Assess risk of contamination of food for consumers.	Support technical, biological, economic and environmental sustainable aquaculture production. Promote good health and welfare for aquaculture species.
Fish escape prevention	Regulation on the operation of aquaculture production sites (Norwegian Ministry of Trade Industry and Fisheries, 2008) Aquaculture Act (Norwegian Ministry of Trade Industry and Fisheries, 2005)	Directorate of Fisheries	Minimise risk of fish escapes and implement systematic preventive measures.	Support technical, biological, economic and environmental sustainable aquaculture production.
Technical condition of fish farm	Regulation on technical requirements to floating aquaculture plants (Norwegian Ministry of Trade Industry and Fisheries, 2011)	Directorate of Fisheries	Assess risks during engineering, manufacturing, installation and operation of fish farm. Include risk of fish escape.	Prevent fish escape by securing the proper technical standard of the fish farms.
Vessel design and equipment; Safety management of daily operations	Regulation on construction and inspection of smaller cargo vessels (Norwegian Ministry of Trade Industry and Fisheries, 2015) Regulation on safety management for smaller cargo vessels, passenger vessels, fishing vessels (Norwegian Ministry of Trade Industry and Fisheries, 2016a) Ship Safety Act (Norwegian Ministry of Trade Industry and Fisheries, 2007)	Maritime Authority	Marine operations, vessel design and stability.	Ensure technical standard of vessels and equipment on board. Systematic, daily management and follow-up of identified risks.
Physical environment	Internal control regulation (Norwegian Ministry of Labour and Social Affairs, 1996) Working Environment Act (Norwegian Ministry of Labour and Social Affairs, 2005) Aquaculture Act (Norwegian Ministry of Trade Industry and Fisheries, 2005)	County Administration Directorate of Fisheries	Sustainability of the aquaculture location and risk for emissions to the surroundings.	Support continuous improvements in regarding the work environment and safety, and protection of the environment against pollution and a proper waste treatment.
Occupational health, environment and safety	Internal control regulation (Norwegian Ministry of Labour and Social Affairs, 1996) Working Environment Act (Norwegian Ministry of Labour and Social Affairs, 2005)	Labour and Inspection Agency	All physical, chemical and biological, organisational, psychosocial and ergonomic elements.	A safe and sound work environment for all workers.

farming fish and keeping them in good health. Risk assessments are statutory and are imposed by five regulatory authorities: The Directorate of Fisheries, Food Safety Authority, Norwegian Maritime Authority, Norwegian Labour Inspection Agency and the County Administration. These bodies are responsible for the regulations regarding fish welfare, food safety, fish farm technical standard, vessel design and equipment, health, work environment and safety, and the environment. The relevant aquaculture legislation and regulations are described in Holmen et al. (2017c) and summarised in Table 1.

2.3. Standards

The requirements for the technical condition of fish farms are described in Norwegian standard NS 9415: Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation (Standard Norway, 2009). Since NS 9415 in itself is not regulatory for the aquaculture industry, the Norwegian Ministry of Trade, Industry and Fisheries (2011) introduced the "Regulation on technical requirements for floating aquaculture plants" in order to ensure compliance with NS 9415. This regulation states that aquaculture installations shall comply with the technical safety level in NS 9415 (or similar) and this is to be certified by an accredited body. The Directorate of Fisheries is the controlling authority regarding the technical components of a fish farm. The standard NS 9415 refers to NS 5814 for risk assessments (Standard Norway, 2008), and the requirements for risk assessments in NS 5814 are thereafter brought into effect. For other areas the standard is voluntary, although some companies have linked their internal risk assessment requirements to NS 5814.

Table 3 shows the steps in the risk assessment process, according to NS 5814. This process is aligned with the risk assessment process of ISO 31000, although not identical.

3. Current practice for risk assessments

3.1. Data collection

The methodological approach in this paper includes data collection from several sources of information; interviews and observations in the field, analysis of risk assessment documentation, as well as four workshops. The information obtained from participants in interviews and workshops has been treated anonymously and has been handled according to the principles of the Norwegian Data Protection Official for Research (NSD, 2018). The methodological approach is described in detail in Holmen et al. (2017c).

3.1.1. Interviews and observations

The interviews and observations aimed to assess the current risk assessment practices at fish farms and on board service vessels. Interviews with workers and observations took place during maintenance and/or daily operations in June and August 2015, June 2016, and March and November 2017 on board four service vessels and at five fish farms. The fish farms are owned by three of the largest Norwegian farmers of Atlantic salmon and located in the three northern aquaculture regions of Norway. Two of the sites are owned by the same company but located in different regions. The service vessels had been chartered to perform maintenance on fish farm structures and moorings.

The vessel crews, fish farmers and operational managers were asked about their involvement in risk assessment and to explain how this is implemented in work practices and safety precautions in daily operations. During the visits, samples of the risk assessment documentation were checked. Additional interviews with HSEQ staff and managers were conducted either by phone or in the informant's office. Table 2 shows the categories of informant, type and number of interviews.

Table 2
Informant categories, type and number of interviews.

Informant category	Individual interview at workplace	Individual interview by phone/in office	"Group interview" in office
Fish farmer	4		
Operational manager fish farm	2		
Service vessel crew	5		
Operational manager vessel	4		
HSEQ coordinator/ manager	1	4	
Management group (4 persons each)			2 (8 persons in total)
General manager		2	
Total	16	6	2

Altogether 24 interviews were carried out, involving 30 persons from six Norwegian aquaculture companies (fish farmers and service providers). These companies vary in size from well-established enterprises with more than 1500 employees to companies of less than 100 workers. Meetings were arranged with two regional management groups; the regional director, the technical manager, the production manager and the HSEQ coordinator in each of two regions of one company. The main purpose of these meetings was to present the findings from the observations at their production units. During the meetings, the management was asked questions regarding implementation of risk management and mitigation measures.

The information gathered through the interviews and observations provided us with an overview of current practices, deficiencies and needs for improved risk assessment in aquaculture.

3.1.2. Documentation

Risk assessment documentation was also gathered from three fish farming companies, in order to identify how the risk matrixes and evaluation criteria were designed according to the regulatory requirements. The documentation is a combination of examples of risk assessment matrixes, descriptions of risk acceptance criteria, and written procedures describing how risk assessments should be performed in the company. This is summarised in Section 3.3.

3.2. Analysis of current practices

This section presents the current practices of fish farming companies regarding risk assessments and compares them with the requirements set out in NS 5814. Table 3 lists the deviations between the recommended steps in the risk assessment process and the current practice in Norwegian fish farming. The qualitative data presented is based on interviews and documentation from six companies (see previous section). The company management is assumed to be committed to the process in their risk management policy. HSEQ staff is often responsible for developing templates or standard checklists as an assisting tool for the operational managers at the fish farms or managers/skippers on board the vessels, who are responsible for carrying out and documenting the risk assessments at their production units. A regional management, which may include a production manager responsible for the biological production, is usually responsible for the implementation of the risk management policies approved by the company's top management. Our study revealed that at some locations the risk assessments were conducted only at managerial level. Risk assessments should be performed before production starts and revised yearly or more frequent if changes are made to equipment, technical installations or operational procedures.

Table 3
The deviations between the recommended steps in risk assessment (RA) according to NS 5814 (Standard Norway, 2008) and the current practice in Norwegian fish farming. The right column specifies which position/management level in the company who is responsible for the step.

Recommended steps in risk assessment process	Deviations	Responsible in company
1. Planning		
1.1 Initiate process, define problem and scope	-RA is not performed before decisions are made. -There is no plan for the work. -There is no description of the background for RA, which parties are involved and how they could be affected.	Management (decisions) ↓ HSEQ staff (suggest, implement)
1.2 Organise the work, establish work group	-No verification of whether there is agreement between the work, the requirements of the standard and the management's specifications. -The working group's competence relevant for the RA is not documented. -The person responsible for RA is not necessarily familiar with the contents of the standard. -The management does not document that the RA has been carried out by competent personnel. -The management does not document that relevant stakeholders are involved.	Production manager ↓ Operational manager (Assisted by HSEQ staff on request)
1.3 Choose method and data sources	-Company internal templates for RA are used, but the choice and sources of data for risk analysis are not verified in writing.	HSEQ staff (preparation of RA template)
1.4 Establish description of system and object to be analysed, document conditions and assumptions	-The object of the analysis is not described in detail. -There is no evaluation of whether premises, assumptions and simplifications are reasonable and realistic.	Operational manager
2. Risk analysis		
2.1 Identify hazards and undesired events	-There is no documentation regarding potential undesired events that have not been not further analysed (e.g. not relevant, minimal risk).	Operational manager
2.2 Analyse causes and likelihoods	-The list of causes identified for each undesired event may not be complete. -RA of technical systems are not complete with respect to human and/or organisational aspects. -There is no documentation verifying that the analysis has been performed at an adequate level of detail based on the objectives and limitations of the RA, decisions to be made, and availability of relevant/accurate data.	Operational manager
2.3 Analyse consequences	-Short-term consequences are dealt with more thoroughly than long-term consequences. -There is no systematic consideration of existing measures which reduce the severity of the consequences, or of other conditions that could influence the outcome of an undesired event. -There is insufficient documentation that verifies that the analysis is concluded at an adequate detailing level based on the objective and limitations of the RA, decisions to be taken, and availability of relevant/accurate data.	Operational manager
2.4 Risk description	-The uncertainties are not assessed and included in the risk description.	Operational manager
3. Risk evaluation		
3.1 Evaluate risks against risk acceptance criteria	-In some cases, the risk may be underestimated.	Operational manager
3.2 Identify mitigating measures and their risk-reducing effect	-The list of measures identified to eliminate, reduce likelihood or consequence of an incident may not be complete. -There is no documentation of the expected effect of measures.	Operational manager
3.3 Document and conclude	-There is no documentation of conclusions from the RA to be used as the basis for risk management. -The documentation neither refers to literature/data sources, nor documents the work process and the choices taken regarding methods, limitations, and possible need for further work. -Deviations from the standard is not justified.	Operational manager

The findings are summarised and commented in section 3.5.

3.3. Risk matrix design and risk acceptance criteria

The standard for risk assessments, NS 5814 (Standard Norway, 2008), states that the description of risks may be quantitative or qualitative, i.e. it is up to the company to choose the preferred method (Table 3). All the companies that participated in this study use qualitative risk analyses and risk matrices to describe risks. The prevailing approach is to describe risk as the product of potential consequences and likelihood. The result is evaluated against risk acceptance criteria expressed by the colours green (acceptable risk - no further action needed), yellow (lowest acceptable risk – consider additional safety measures) or red (inacceptable risk – risk-reducing measures shall be implemented). The risk priority numbers (RPN) are suggested by personnel in the HSEQ department and decided by the management. One of the companies performs risk assessments along eight consequence dimensions: fish health, fish welfare, fish escape, human health and safety, reputation, food threat, food safety, environment. Table 4 shows examples of risk-matrix designs in three companies. The consequences depend on the area analysed, and in Table 4, the consequences for health, safety and work environment (HSE) are used for comparison.

3.4. Informal risk analyses

Safe job analysis (SJA) is a risk-analysis method that is performed to identify potential hazards during operations, and to implement measures which reduce the risks (Rausand, 2011). SJA should ideally be carried out by the work team prior to the operation, and is usually carried out for less frequent, hazardous operations, dangerous routine jobs or new procedures. Other triggers for a SJA might be a new vessel or new operators participating in a complex operation. Important objectives of SJA are to make operators more aware of inherent risks, and to discuss possible actions to mitigate undesired events.

SJA was originally a process comprising several steps and with thorough documentation of the risk assessment of each task within the operation (Rausand, 2011). Some fish farm companies have implemented a template for a SJA "light", which assumes that a risk

Table 4
Risk matrix design and risk evaluation criteria as defined by three fish farming companies.

Company no	Size	Type of risk	Consequence priority number (example HSE)	Likelihood	Risk priority number (RPN)
1	5 × 5	Fish health, fish welfare, escape, HSE, reputation, food threat, food safety, environment	1 = Insignificant, no absence 2 = Minor, absence < 3 days 3 = Significant, absence 3–14 days 4 = Serious, long time sick-leave, permanent injury 5 = Catastrophic, fatal	1 = Very unlikely (once every 10th year or less) 2 = Less likely (once in 1–10 years) 3 = Likely (once per year) 5 = Quite likely (1-10 times per year) 10 = Very likely (More than 10 times per year)	≤ 4 Acceptable risk 5 < 10 lowest acceptable risk. Preventive measures shall be implemented, further mitigations to be considered. ≥ 10 Unacceptable risk. Risk-reducing measures must be identified and implemented before operation can start.
2	6 × 6	Fish health, fish welfare, HSE, food safety, external environment, environmental aspects	1 = No injury 2 = Minor injury, no medical treatment 3 = Minor injury with medical treatment 4 = Serious injury 5 = Serious injury, long time harm 6 = Fatal	1 = Not likely at all 2 = May have happened 3 = Yearly 4 = Monthly 5 = Weekly 6 = Daily	≤ 6 Acceptable risk 8-16 Lowest acceptable risk. > 16 Unacceptable risk.
3	5 × 5	Fish welfare, escape, personnel safety, reputation, food safety, environment	1 = Very low, no injury 2 = Low, injury with no absence or reported to NLIA[a] 3 = Medium, absence injury and/or reported to the NLIA 4 = High, permanent injury 5 = Very high, permanent disability or death	1 = Extremely low, never heard of 2 = Low, have heard of 3 = Likely, may happen once 4 = Much likely, may happen a few times 5 = Very likely, may happen several times	≤ 4 Acceptable risk 5 < 15 Risk-reducing measures may be implemented ≥ 15 Unacceptable risk. Risk-reducing measures shall be implemented.

[a] Norwegian Labour Inspection Agency.

assessment for the work operation or procedure already exists. The "light" version is then a way to remind the personnel of the operational risks, as well as to update the procedure if it has been a while since it was last used.

One of the companies in this study has a written procedure for SJA, which states that SJA must be carried out ahead to all work operations that a) are not already described in a procedure; b) have not been conducted for a long time; and c) for which personnel lack relevant experience/training. Another company calls all personnel in to a "pre-operation meeting", in which the risk assessments are presented and a memo subsequently documents the content of the meeting. Some operational managers have an informal meeting which has previously been referred to as the "cup of coffee chat" (Holmen et al., 2017c). Although such meetings are not a SJA as described in the literature, the intention of the risk analysis method is achieved: bringing together all operators, both in-house and hired services, reminding them of the operational hazards, discussing responsibilities, sharing knowledge and agreeing on safe job practices. When this study began, SJA was new to several of the companies, and their staff had little knowledge of how to run a SJA. However, during the two years of data collection, more companies have started to do SJAs regularly and have established internal templates or checklists as a tool for their operations managers.

Some aquaculture companies report that planning operations is a challenge, involving complexities due to changes in the weather, attacks by fish parasites and other biological factors, as well as the availability of experienced operators, well-boats or other essential subcontractor services. The industry is therefore seeking tools to support good practices for operational planning. A systematic SJA process in good time could therefore be a useful means of mapping and identifying the most important risk factors involved in the operation.

3.5. *Summary of findings*

The largest gaps between the recommended steps for risk assessments in NS 5814 and current practice were found in the planning phase, and regarding the involvement of workers in the analysis phase. In many cases, risk assessments were not properly planned or given sufficient priority during day-to-day farming and maintenance tasks. The involvement of operators turned out to be in sufficient or completely lacking. This is an important part of the risk assessment procedure that needs be improved to achieve the regulatory requirement of operator involvement in internal control (Norwegian Ministry of Labour and Social Affairs, 1996).

In the risk analysis step, the hazards were listed but the chains of events were not thoroughly described. Nor was it clear how well the risk assessments were related to actual work practices. The persons responsible for the risk analyses often had little if any documented formal training. Moreover, the methods for identification of hazards were often based on templates, which might not be connected to the different operations which are the sources for the potential hazardous events. In general, documentation of details in the work process, choices and limitations taken, was not satisfactory according to this standard.

All the companies that participated in our study employed semi-quantitative descriptions of risks in matrices, and used worksheets to keep track of possible hazards and their sources, causes, likelihoods and consequences. The number of types of risk as well as the design of the risk matrices differ somewhat between the companies. Neither the consequence priority numbers nor likelihood grading (expressed as frequencies) are standardised within the industry. Hence, the risk priority numbers (RPN) vary significantly and are not comparable between the companies.

Sufficient involvement of operators may not be prioritised when there are practical tasks that need to be done. This is compensated for to a certain extent by the introduction of safe job analyses (SJA). An SJA is carried out prior to operations that are regarded as being of particularly high risk, because they are rarely performed, previously described in written procedures (e.g. introducing new equipment or techniques), or if the personnel have only limited experience of the particular operation to be performed. SJA was gradually implemented in the fish farming industry during the study period.

4. Improving risk assessment practice - closing the gaps

4.1. A new approach

In this section, suggested improvements are first described for each main step of the risk assessment process, as described in NS 5814 (Standard Norway, 2008): planning, risk analysis and risk evaluation (Table 3). This is then summarised in a stepwise recommended approach aimed at closing the most essential gaps identified during the comparison with the requirements for risk assessments in NS 5814 (previous section).

4.1.1. Planning

To ensure that risk assessments are well anchored in the organisation, stakeholders must be properly involved in the planning process. An organising team should be appointed by the top management and given responsibility for planning and conducting the risk assessments. If the risk assessment is performed at a fish farm, the operational manager should be responsible. The safety representative elected by the employees, a duty statutory in the Working Environment Act (Norwegian Ministry of Labour and Social Affairs, 2005), should also be involved. It is necessary to have personnel experienced with risk assessments in the group, e.g. HSE personnel. The group shall define problems and the scope of the work and specify which types of risk are to be assessed. The group should also decide on a method for hazard identification and risk analysis, and this should be suitable for the data sources available, system/object and risk type to be analysed. If a template for risk assessment is used, feasibility must be assessed, and if necessary, revised.

4.1.2. Risk analysis

Current practice for the risk analysis step is close to the requirements of the standard, as is to be expected because it is usually regarded as the "core" of the risk assessment process. The documentation of risk assessments is largely based on this step. One necessary improvement is to identify hazards and undesired events associated with the various tasks that make up an operation, including the use of equipment. Implemented risk-reduction measures must be taken into consideration. Today's prevailing practice is to pick these out from a template or to list hazards and undesired events without the operational context, which in itself might influence the risk level. A template should only be used as a checklist for possible hazards or undesired events, as well as for possible actions to mitigate risks.

4.1.3. Risk evaluation

The evaluation against risk acceptance criteria need not be a central task for the entire work group, as in practice it might end up as a mere "exercise" to avoid "red" entries in the risk matrix. The organising team, and/or HSE personnel, may finalise this step. The contribution of operators should be aimed at identifying additional safety barriers and other mitigating measures in order to reduce the likelihood or consequences of high risks, as well as prioritisation of measures. This task should be prioritised when limited time is available for gathering all the personnel involved. Operator participation in this step can be ensured by involving the safety representative or another person representing the operational staff. In many cases, the operations manager has considerable experience with the operations, as he/she has often started working as an operator. Table 5 is a stepwise summary of the suggested improved approach for risk assessments in the industry. NS 5814 should be used as a reference. The following section describes the testing of this approach at four workshops.

4.2. Testing and evaluation of the approach: workshops

The improved approach outlined above was tested and evaluated in four workshops with industry participants. The practical organisation of the workshops have previously been described in detail by Holmen et al. (2017c). The steps of the NS 5814 risk-assessment process were followed, and the process was organised as shown in Table 6.

Table 7 (adapted from Holmen et al. (2017c)) lists the number and category of participants in each of the workshops, as well as the service vessel operations that were the topics of each workshop. These operations were identified as being of high operational risk, based on current analyses of occupational accidents and fish escapes, as well as the participants' own experience and perception of hazards. All these operations involve the use of winch and/or cranes. In workshop 3 it was decided to analyse "preparations for fish transfer" and "maintenance operations", which include several of the other operations. Lifting of coupling plates precedes anchor setting and/or tightening of moorings. Delousing involves lifting of the sinker tube, which is also an initial stage in the preparations for fish transfer. No templates were used in any of the workshops. The risk analysis method in the workshops was based on the preliminary hazard analysis described by Rausand and Utne (2009). The focus for hazard identification was limited to risks to personnel and escape of fish.

The above activities cover steps A–C in Table 5. The next step was to gather operators and managers to do the risk analyses. Up to four operations were analysed per workshop (Table 7). To do this efficiently, the participants were divided into groups, each of which described one operation. The groups were initially placed at separate tables (Holmen et al., 2017c). After a while, the groups rotated to the next table and added information to the description by the previous group. The work operations (object of analysis) were thus described in detail by all the participants, and a thorough description of the work tasks and involved objects/tools was produced. The results showed that while the operations usually were performed in accordance with the written procedures, a few major discrepancies at certain stages were also revealed. These were dealt with as a part of the following risk analysis process.

The second assignment for the groups was to identify hazards and undesired events associated with each operation described above (step F in Table 5). Again, each group started on one operation, and rotated to the next table until all the operations had been analysed. This was repeated for the analysis of causes, likelihoods and consequences, and identification of mitigation measures (step G). Steps G–J were finalised in workshops 1 and 2, but were not fully tested in workshops 3 and 4. In these workshops, each hazard/undesired event, possible causes and consequences were assessed qualitatively. The priority in the workshops was to establish thorough descriptions of the operations, and to identify hazards and undesired events associated with each task of the operation. The operators were involved throughout the process of listing existing safety barriers/measures and suggesting further risk-reduction measures, as this also increased their understanding of how safety can be improved in their daily work. The organising team documented the process (step K).

5. Results and discussion

5.1. Current practices for risk assessments

5.1.1. Implementation challenges

The aquaculture industry is obliged to perform and document risk assessments in accordance with the legal framework presented in Table 1. Complying with requirements from five authorities is a time-consuming and resource-intensive task. The priorities of the companies involved in the interviews and workshops were found to be affected by possible damage to the profits or the reputation of the industry. The media's often negative attitudes to the fish farming industry has been shown not only to influence the public, but also to limit the regulatory

Table 5
Stepwise specification of the suggested improved approach for risk assessments in the fish farming industry. The suggested process aims to close the gaps identified between current practice and the requirements in NS 5814 (Standard Norway, 2008).

	Improved approach	Comment
Planning		
A	Establish an organising team appointed by the company management.	Include HSE personnel with training in risk assessments, who will be responsible for documentation. The farm operational manager is responsible, and the safety representative should be involved.
B	Identify work operation(s) of high risk.	Should be based on operational experience and incident reports.
C	Decide which type(s) of risk to assess. a If applicable, assess and revise template. b Choose a suitable method for risk analysis according to the type of risk to be assessed.	Should be specified in company risk management procedure; e.g. fish welfare, HSE, food safety (see Table 4).
D	Gather a group of operators and managers responsible for performing the operations.	Workshop with operators: Mix fish farmers and service vessel crews if possible and relevant for the operations involved.
E	Describe operations at individual task level, including critical gear/ equipment used. Agree on safe job practices.	HSE personnel should update the written work procedure if deviations are identified and justified.
Risk analysis		
F	Identify hazards and undesired events associated with each task/ equipment.	Workshop with operators.
G	Analyse causes and likelihoods for each hazard/event, taking existing risk-reducing measures into consideration. Analyse consequences.	Workshop with operators.
H	Describe risks in terms of product of potential consequences and likelihood.	Organising team may perform this step.
Risk evaluation		
I	Evaluate risks against risk acceptance criteria.	Organising team may perform this step.
J	Identify additional mitigating measures to be taken and evaluate their risk-reducing effect.	Mitigating measures should be discussed at workshop. The organising team may perform the evaluation of risk-reducing effects.
K	Document risk assessment process.	HSE personnel.

Table 6
The involvement of personnel in the risk assessment process.

Step in NS 5814 (Standard Norway, 2008)	Organising team	Workshop (operators, HSEQ staff and managers)	HSEQ staff
Planning	X	X	
• Initiate process, define problem and scope	X		
• Organise the work, establish work group	X		
• Choose method and data sources			
• Establish description of system and object to be analysed, document conditions and assumptions			
Risk analysis	X	X	(X)
• Identify hazards and undesired events		X	
• Analyse causes and likelihoods		X	
• Analyse consequences		(X)	
• Describe risk as a product of potential consequences and likelihood			
Risk evaluation	X	(X)	(X)
• Evaluate risks against risk acceptance criteria	X	X	(X)
• Identify mitigation measures, compare alternatives and their risk-reducing effect			
• Document and conclude			

Table 7
Work operations for risk assessments discussed in the workshops, including number and category of participants: Managers (M), fish farmers (F), service vessel crew (S), technology providers (T).

Workshop no.:	1	2	3	4
Participants:	M F S	M F S	M F S T	M F S T
No. of participants:	20	17	12	13
↓Operations				
Clean floating collars	x			
Tighten moorings	x			x
Set and fasten anchors in seabed	x	x		
Swim fish between net cages		x		
Mount nets in cages		x		
Lift coupling plates	x	x		
Preparations for fish transfer			x	
Maintenance operations			x	
Lift sinker tube				x
Remove old moorings				x

focus on sustainability to environmental risks (Olsen and Osmundsen, 2017). The present study shows that most efforts are put into the documentation of actions to mitigate environmental hazards, i.e., fish escapes.

Several challenges were identified regarding current risk assessment performance. First, the companies find it difficult to allocate sufficient time to gather all relevant personnel for risk assessments. As a result, at some fish farms this may be done only at managerial level. Second, some of the participants lack motivation and see it as an unavoidable "exercise" to satisfy the demands of the authorities or their own management. Third, finalising the risk documentation is regarded as more important than checking whether the significant risks are understood and mitigated. Fourth, the scope of the risk assessments is broad. It may take several days to perform assessments of all types of risk as regulated by the authorities. Any prioritisation is affected by public opinion and consumers' concerns, and possible sanctions by the authorities. Fifth, once the risk assessments have been finalised, the follow-up work with detailing of action plans and improvements of procedures may not be prioritised, giving the wrong signal back to the organisation that the only point of the risk assessments is to satisfy the documentation requirements in the regulations. These challenges are further addressed in the following sections.

5.1.2. Variable quality and content

The information that we gathered through interviews and observations shows that the quality and implementation level of risk assessments vary considerably, between both companies and different sites run by the same company. Some companies, typically the larger ones with well-established safety management functions and trained staff to maintain the systems, have implemented computer-based, online systems for quality and safety management, and have written procedures on how to perform risk assessments, specifying the types of risk that are to be included. The smaller companies are, so far, less systematic in documenting the activities required of them. There are also observations that suggest a lower level of implementation on board service vessels than at fish farms. Several of our informants had not personally been involved in the risk-assessment process, and work was still under way to complete the risk assessments for some vessels. The vessel operators explain that this is because they have less time available for safety management on board. The operations managers at the fish farms also have more predictable working hours, in some cases more or less "fixed" office hours, and have access to an office and to online quality-management systems. Service providers are experiencing a growing demand from fish farming companies to document work operations and compliance with safety requirements, and this is likely to be a driving force for subcontractors to the fish farming companies to implement systematic risk management and risk assessments.

The risk assessments that we studied without exception are semi-quantitative and are described in risk matrices. These are known to have limitations, as they are mainly based on subjective assessments that depend on individual experiences (Cox, 2008). Public reports on fatalities, serious occupational injuries and fish escape may be used as qualitative input to the assessments. As an easy tool to visualise and document the outcome of the hazards identification and risk analysis process, risk matrices serve their purpose for aquaculture companies, as long as they understand their limitations.

5.1.3. Level of implementation

A recent survey of safety management practices among management and office staff in the Norwegian aquaculture industry investigated several aspects of safety management implementation (Kongsvik et al., 2018). A total of 135 persons from 15 companies participated in a web-based survey, and risk assessment and SJA was among the topics. For example, the following question was asked; "Have formal risk assessments for the work at the fish farm been carried out during the past four years?" As many as 98% of the respondents responded positively to this, and 86% reported that all employees participate in the risk assessments, while 81% said that risk assessments are actively employed to reduce occupational risks. These numbers are relatively high compared to the feedback from the participants in the qualitative study described here. However, the survey was aimed at managerial level, and the answers might well have been different if the operator level had been asked the same questions.

The situation in the aquaculture industry regarding the risk of occupational injury does seem to be improving (Holen et al., 2018a), as well as fish escape. Escapes of farmed fish have significantly diminished since 2006 (Directorate of Fisheries, 2017b). The major cause of fish escapes is holes in the net (Føre and Thorvaldsen, 2017), which indicates that risk assessments should be focused around events which lead to tearing of nets. One explanation for the reduction in escapes is that the authorities have improved their inspection routines. Another is that the industry, which is rapidly growing, needs to improve its reputation in order to recruit qualified workers. This increases the motivation for top management to allocate sufficient resources to risk management. According to industry representatives, a fewer incidents happen during complex operations than before, and this is explained by improved routines for planning and comprehensive risk assessments. However, the safety management survey showed that there still is room for improvement (Kongsvik et al., 2018).

Compared to other ocean industries such as the offshore petroleum sector, safety management systems in fish farming are not yet as comprehensive (Holmen and Thorvaldsen, 2015). Fewer resources are allocated and motivation for performing paper-work is low. A more practical approach to improving the impact of risk assessments, and in turn risk management, would therefore be beneficial for this industry.

5.2. Closing the gaps

The following section, "Improved approach to risk assessments", discusses improvements regarding operator involvement and hazard identification. Planning, time and resource allocation are addressed in the section "Limited resources require efficiency and good planning" (5.2.2). Different aspects of documentation are discussed in all sections. Templates are specifically addressed in "Additional recommendations" (5.2.3).

5.2.1. Improved approach to risk assessments

The intention of the risk assessment process is to systematically gain a greater understanding of the risk situation in the work environment. The operational staff have the practical experience, and they daily face the hazards and make decisions to prevent accidents from happening. As the improved approach recommends, their involvement should start at the stage where the system is described, by mapping the stages in the operations, which they know well, and thereafter by identifying the hazards associated with each stage. Causes and consequences should also be discussed in groups that include operators, managers and HSEQ staff. Thus, if the managers follow up by documenting the process and establishing a shared action plan for risk-reducing measures, an important part of the regulatory internal control will have been implemented (Norwegian Ministry of Labour and Social Affairs, 1996).

The process of describing risks and evaluating them against risk acceptance criteria can be finalised by the operational management supported by HSEQ personnel. Decisions on which preventive measures to prioritise are closely connected to budget discussions at management level, and the suggested approach will ensure that the management is familiar with levels of risk in the workplace. In audits or accident investigations, the risk assessments are used by the authorities as a quality indicator of the risk management. They will also record which risk-reducing measures the company has identified and perhaps implemented. It is therefore essential that companies can document that they have performed thorough risk assessments as the basis for mitigating risks inherent in the work environment on vessels and at fish farms.

The workshops (Holmen et al., 2017c) produced detailed descriptions and risk assessments of work operations and equipment, as well as a list of preventive and risk-reducing measures. A common understanding of the work environments and operations was established between the operators and managers. An example is how the coupling plate should be lifted out of the sea. The correct way to do this is to attach the crane to the chain which connects the buoy to the coupling plate, and not lift the buoy itself, unless the buoy is certified for lifting. The added hazards of this irregular procedure were thoroughly discussed. Differences in procedures might also be explained by the kind of equipment that is available at each fish farm. Participants appreciated having the opportunity to exchange their experiences across regions and companies. This was an added value of the new approach. Industry associations may take this further and develop industry standards for risk assessments and knowledge sharing. The Norwegian construction industry is a good example of this, as it has already developed a collective standard for risk assessments of construction work; NS 5815

(Standard Norway, 2006).

The most important improvement due to the approach presented in this paper, compared to established practices, is the strong involvement of the operators. This is a requirement described in the internal control regulation. The use of group discussions and of documenting input on flip-over sheets lowers the threshold for contributions from everyone. Furthermore, the focus is shifted from lowering the RPN to acceptable levels, towards a shared understanding of the need for measures that can eliminate hazards or reduce the consequences of any incidents that do occur. This approach thus supports the overall goal of the required risk assessments, which is to identify means of reducing risk to fish welfare, food safety, and technical and personnel safety at aquaculture workplaces. These risk assessments can thus also be used as a tool for operational planning, as well as a basis for safe job-analysis checklists.

Furthermore, the organisation of the workshop, with several groups providing input to the different operations in turns, resulted in more comprehensive recordings of the hazards than any group would have produced on its own. This can be achieved in a company by gathering operators from several fish farms and/or service vessels. This will also be an arena for organisational learning, as the operators can exchange experience and knowledge regarding safe and efficient job practices. Finally, it is likely that needs and ideas for improved engineering solutions that eliminates hazards are identified. The results of systematic risk assessments are thus of high interest also to manufacturers of equipment. This was demonstrated when technology providers were invited to two of the four workshops (Holmen et al., 2017c).

5.2.2. Limited resources require efficiency and good planning

The greatest challenge to performing high-quality risk assessments is probably that of allocating enough time to involve the operators sufficiently according to the Internal Control Regulation (Norwegian Ministry of Labour and Social Affairs, 1996) and NS 5814 (Standard Norway, 2008). Competent and committed managers are required in order to involve the operators properly. Qualified HSEQ staff should ideally be of support to the operational managers during the risk assessment process and be a driving force in the organising team. The larger companies usually have such personnel available who could relieve the operational manager from some of the planning activities. In the smaller companies, several management functions may be gathered on one person, thus making it hard to allocate time for a proper risk assessment involving the operators. The suggested improved approach is not less time-consuming; however, it can increase the efficiency of the process in that a more comprehensive list of risks and mitigation measures are documented. Furthermore, the learning outcome of the process is likely to be greater because each operation and its inherent hazards are analysed in detail: a common best practice is put in writing, the operators take part in the identification and description of causes, consequences, likelihoods, risks, risk-mitigating measures and evaluation of their effect.

During the fish production phase, which lasts for approximately 18 months, there are few available time windows for this resource-intensive work. Usually there are two teams at each fish farm working shifts, although only one operational manager and at some farms, a deputy manager. One strategy could be to treat risk assessment efforts as a mandatory seminar and bring the off-duty team together away from the fish farm for a couple of days. This can be done at intervals until all relevant operations and components have been analysed. However, this may come in conflict with the Working Environment Act's regulations on the maximum permitted working hours per week and month (Norwegian Ministry of Labour and Social Affairs, 2005). The work shifts at fish farms are already carefully tuned to be in line with the requirements (Thorvaldsen et al., 2017).

Another strategy would be to allocate time for updating risk assessments between fish generations, which is normally a period of two or three months. However, during this period of no fish to farm, major maintenance activities to prepare for the new stock are scheduled, and the focus is therefore on the technical aspects of planning the next production cycle. The risk assessments are the basis for an efficient risk management both at the fish farm as well as in the company. Ideally, the company management should plan the production cycles so that the fish farm personnel are also given sufficient time to update the risk assessments.

5.2.3. Additional recommendations

Several of the companies that participated in this study have designed templates which are adapted to each vessel or farm. Using a template can increase the effectiveness of the risk assessment process, since possible hazards, causes and consequences are already listed for different systems and the template serves as a checklist. Regular updates based on the outputs of risk assessments performed as recommended in this paper will improve both the content and the impact of the templates. A thorough template based on best operating practice could simplify risk assessment updates for complex operations, e.g. when new technology or maintenance schedules are implemented, or a new crew joins a vessel.

The use of safe job analysis (SJA) has increased during the past few years, as it is recognised that this is a useful tool for a carrying out systematic risk analysis in operations, i.e. stepwise mapping of hazards, causes, consequences and risk-reducing measures associated with a given work task or operation. However, at present, there are probably as many versions of how to perform SJA, both in content and template for documentation, as there are aquaculture companies. The petroleum industry has introduced recommended guidelines for SJA (Norwegian Ministry Of Trade, Industry And Fisheries, 2017). These guidelines describe step by step how to conduct SJA, and could be adapted for use in the aquaculture industry to establish a common procedure. An SJA performed as described in these guidelines would to largely satisfy the requirements in the planning and risk analysis steps of the risk assessment process described in NS 5814. SJA is therefore a suitable methodology for risk assessment of operations (see step C in Table 5).

As Section 2 mentioned, the regulatory requirements for risk assessments are fragmented, as they are statutory instrument promulgated by five different authorities (Holmen et al., 2017c). Risk management is therefore dealt with in separate parts of company management systems. These are also audited separately, although the Directorate of Fisheries and the Food Safety Authority coordinate inspections because they are regulatory authorities for separate parts of aquaculture legislation (Table 1). Yang et al. suggest that five dimensions of risk should be considered in a single risk-management system; risk to personnel, risk to material assets, risk to fish welfare, risk to the environment and food safety. There is thus a potential for merging the requirements of the individual sets of regulations into a unified management system. The aquaculture industry should be encouraged to establish common regulations and guidelines for a holistic risk-management system, which would combine all relevant types of risk.

6. Conclusions

This paper describes and discusses the implementation of risk assessments in the Norwegian aquaculture industry, and compares the current practice with the recommendations in the Norwegian standard NS 5814 (Standard Norway, 2008). An improved approach to risk assessment was suggested and evaluated.

Previous studies show that the Norwegian aquaculture industry has safety challenges which could be mitigated by systematic risk management, of which risk assessment is a core activity. An aquaculture industry standard for risk management across the regulatory disciplines is lacking, while other sets of regulations may include safety requirements that address similar objectives. This results in a fragmented approach to risk assessments. Practices for risk assessments differ greatly between companies in the Norwegian aquaculture industry. There is therefore a potential for making significant improvements to the situation by implementing a systematic and standardised approach to risk assessments.

The comparison between the recommended steps for risk assessments in NS 5814 and current practice found the largest gaps in the planning phase, and regarding the obligatory involvement of workers in the risk analysis phase. Operator involvement was often either inadequate or missing. Furthermore, the link between operations as a source of risk and risk assessments was not clear, especially if the template did not support the breakdown of operations into tasks. Finally, documentation was unsatisfactory according to the requirements in the standard.

We developed and tested an improved approach to risk assessment based on preliminary hazard analysis in cooperation with the aquaculture industry (Holmen et al., 2017c). The largest difference compared to current is that our approach describes each operation in detail, assesses the hazards, describes and evaluates the risks associated with each task, instead of merely listing general hazards and assigning risk levels to them. Hazards associated with known high-risk operations as cranes and winches were thus described in the relevant context. This approach will increase the likelihood for identifying possible new hazards arising if the lifting operation is changed or if the crane is used in a new setting. This approach has been tested and evaluated in a series of workshop and demonstrated a high level of involvement by the operators. The outcome of the process was not merely a comprehensive list of hazards and mitigating actions. According to the operators, they appreciated the opportunity to discuss best practices with colleagues and operators across regions and companies. Thus, the improved approach as described in this paper also contributed to an improved common understanding of how operations should be performed with safety in mind.

Declaration of interest

None.

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Article 5

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Identification of safety indicators in aquaculture operations based on fish escape report data

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ABSTRACT

Finfish farming is the most common aquaculture mode in Europe. In Norway, the industry faces sustainability challenges. One major challenge is fish escape, which is a threat to both the environment and the industry's reputation. The more complex the operation, the greater the risk of escape, and their safety management needs improvement. A recommended strategy is to implement a safety indicator programme to monitor the risk levels before, during, and after an operation.

The main objective of this study is to identify risk influencing factors (RIFs) and develop safety indicators for fish farm operations based on accident reports, using a qualitative graphical network to visualise and systematise causal chains. We have used a six-step methodology to develop safety indicators that can be applied to the case of fish escape: 1) The study was limited to fish escape accidents caused by the hazardous events *hole in the net* and *submerged net*. 2) Operations of high risk were identified, and chains of events were established, starting with these operations and ending with the accident (fish escape), based on fish escape report data and accident analyses. 3) A qualitative Bayesian network (BN) was drawn to specify the influence between the contributing causes and conditions in the causal chains. 4) RIFs were identified based on the BN (seven environmental, four organisational, eight operational, and 12 technical). 5) Safety indicators were developed to measure the condition of the RIFs. Update frequency of indicators, methods of measurement, and recommended states were also suggested. 6) The safety indicators were evaluated according to the chosen quality criteria. Based on the resulting list of safety indicators, we suggest a safety indicator programme for the operation *fish crowding*.

The causal chains, RIFs, and safety indicators can also be used as a supplement in internal audits and quality improvement work, development of preventive measures, and training of fish farm personnel.

1. Introduction

1.1. Background

The aquaculture sector is the fastest-growing food industry globally (FAO, 2018), and has overtaken capture fisheries in terms of mass-produced seafood in 2014 (Clavelle et al., 2019). In Europe, finfish farming is the most common aquaculture activity. Atlantic salmon and trout together account for 99.6% of the total biomass production in Norway (Holmen and Thorvaldsen, 2018). Atlantic salmon is by far the dominant species in Norwegian sea-based farming, accounting for 93% of it. Norway is the number one global producer and exporter of farmed Atlantic salmon (FAO, 2019).

Although aquaculture is being presented as a solution to the future global food gap, some major safety challenges must be overcome to enable sustainable growth in the industry. Due to these obstacles, the Norwegian aquaculture production has stagnated over the last few years, and the production cost has increased (Directorate of Fisheries, 2019). There are multiple challenges. The technology must be improved to enable safe and environmentally friendly production at offshore production sites (Bjelland et al., 2015), and to prevent fish escapes, which might be a threat to the wild salmon stocks and might create occupational and financial risks (Jensen et al., 2010; Thorvaldsen et al., 2015). Other challenges are connected to negative publicity about food safety and the sustainability of the industry (Olsen and Osmundsen, 2017). Fish welfare is also a concern, and levels of pests such as sea lice should be monitored regularly (Nilsson et al., 2018). Furthermore, there are health and safety issues when it comes to occupational risk in marine operations (Holen et al., 2018a; Holen et al., 2018b; Thorvaldsen et al., 2020). From a holistic perspective, there are five dimensions of risk to be

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considered: risk to material assets, to personnel, to fish welfare, to the environment, and to food safety (Yang et al., 2020b). Risk management strategies should integrate all these dimensions, as well as the sustainability perspective (Utne et al., 2017).

When operations continue for hours or days, additional safety measures are needed to capture hazards emerging from changing operational conditions. Furthermore, risk reduction strategies may be different during the phases of operation planning and operation execution, or if an emergency occurs (Yang and Haugen, 2015). Risk levels should therefore be monitored during the operation, either continuously or at intervals, to provide updated information for qualified decision support about how to improve operational safety.

Safety indicators are observable measures used to monitor the condition of technical systems, to measure personal safety levels, and to assess the safety management and practices in organisations (Kongsvik et al., 2018). Safety indicators and risk factors may be identified from different sources, such as accident registrations, accident investigations, audit reports, nonconformity databases, hazard identifications, risk assessments, and expert judgments from experienced operators and managers. The practical use of safety indicators to detect increasing risk and give early warnings is important in the working life (Kongsvik et al., 2018). Safety indicators have been developed in the oil and gas industry to measure the changes in safety levels as a function of time, so as to identify increasing risk of, for example, blowouts (Skogdalen et al., 2011).

The governance of the fish farming industry today uses a few standardised safety indicators. They are used by the regulatory authorities to manage sustainable growth in the industry, and by companies to plan operations, monitor fish welfare, and improve internal procedures. The numbers of occupational accidents and injuries are recorded by the Norwegian Labour Inspection Agency and the Norwegian Maritime Authority, which are responsible for health, safety, and the work environment at fish farms and on-board vessels, respectively. The environmental impact of fish farming is regulated by the County Administration/Governor at a regional level, based on systematic measurements of the benthic impact of each fish farm (Standard Norway, 2016). Fish welfare indicators, like water quality, oxygen levels, temperature, and salinity, have to be systematically monitored by the fish farmer to ensure good living conditions for the fish (Ministry of Trade and Fisheries, 2018). The salmon lice levels are used as an indicator for fish welfare by the Food Safety Authority (Ministry of Trade and Fisheries, 2016). They are also used by the government to decide whether to increase the farmed fish biomass capacity in the production zones of Norway (Kristoffersen et al., 2018; Ministry of Trade and Fisheries, 2017a). The Directorate of Fisheries is the regulatory authority for the aquaculture industry in Norway, which issues licences to operate and monitors fish farm structures and fish escape. All fish escapes must be reported, including the number of lost fish, the type of fish farm, and the direct and contributing causes. The Directorate uses this information to improve the regulatory requirements and to highlight the hazards that the fish farmers should take precautions against. Fish escape events are related to both production loss and insurance claims (Jackson et al., 2015), potential penalties and a major reputational risk to the industry. Prevention of escapes hence also have considerable economic incentives within the fish farming companies. The mitigations have traditionally targeted technological and procedural improvements, but changes to the risk levels during operations are still unknown.

The operations are often complex, and many factors influence the operational risk level (Holmen et al., 2017b; Holen et al., 2018c; Yang et al., 2020b; Utne et al., 2017; Yang et al., 2020a). For example, the wind direction affects the success of a crane operation, and if the wind is a problem, the operators have to decide either to postpone the operation until the wind has changed, or moor the service vessel in a favourable position to minimise the negative effects. Experienced operators on the fish farm already know this, although it might not be documented in a written procedure. When there are many risk influencing factors, a more systematic tool is needed to identify hazardous conditions and possible preventive actions, but such a tool does currently not exist for use in the aquaculture industry. The key question is, Which important risk influencing factors and safety indicators should be monitored in order to prevent hazards and reduce the negative consequences of an hazardous event?

1.2. Objective

The main objective of this study is to identify risk influencing factors and safety indicators in fish farm operations. The methodology is based on accident reports, and a qualitative network is used to visualise and systematise causal chains.

A systematic approach to identifying risk influencing factors will increase the knowledge of operational hazards and undesired events and hence be used to improve safety management in aquaculture companies. Furthermore, the safety indicators can support decision-making about targeted and effective risk reduction measures during operations. This study is based on fish escape events, which are related to fish welfare and environmental impact. However, the operations also involve risks to workers, fish farm structures, equipment, and vessels.

2. Assessment and monitoring of operational risk

2.1. Current Norwegian fish farm technology

A good understanding of the technology and operations is needed to identify the hazards and operational challenges in today's fish farming. The typical salmon farm consists of a feed barge and 10–12 net cages, each containing up to 200,000 salmon (Holmen et al., 2018). At present, cylindrical net cages are the most common type used in Norwegian fish farming. Fig. 1 is an illustration of a typical fish cage. The net cages are 22–100 m in diameter, 70–314 m in circumference, and 15–30 m deep. The upper part is fastened to a collar made of black polyethylene tubes, which keeps the cage floating in the water and creates a circular opening. The floater consists of double collar tubes and a handrail tube. A gangway is attached to top of the floater to ensure safe access around the net cage. The net cages are moored to a grid of heavy-duty ropes, with coupling plates joining the cages and mooring lines together. The outer frame of the mooring grid is anchored to the sea bottom. The bottom weight is an important part of the stretching system, which maintains the cylindrical shape of the net cage. It consists of a circular sinker tube fastened to the bottom part of the net. The bottom weight is also connected to the upper part of the net cage with vertical ropes used to lift the stretching system when crowding the fish. These operations are carried out with cranes from service vessels moored alongside the net cage.

Regular maintenance of the net cage is important to keep the fish safe

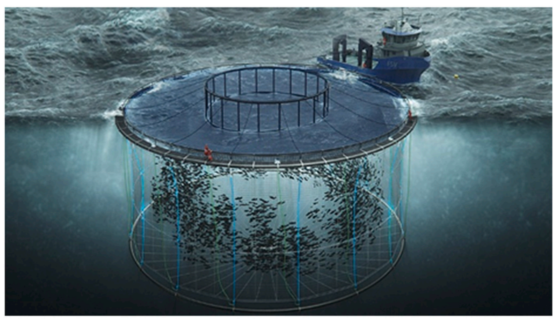

Fig. 1. Illustration of a circular net cage with attached components (permission from Scale AQ).

and healthy. The operations related to the fish production are conducted by the fish farmers (e.g., daily monitoring the fish welfare, feeding, lice counting, removal of mort), while specialised service vessels and crews perform most of the periodic maintenance tasks (e.g., removal of biofouling on the net pen, maintaining the moorings, delousing). Large well boats are hired to transport fish to and from the fish farm, and to assist during delousing operations or disease treatment. It is necessary to manage the risks related to both the fish farm technical conditions and the manned operations.

2.2. Important concepts

Four decades ago, Kaplan and Garrick (1981) defined risk as the combined answer to three questions: *1) What can go wrong? 2) What is the likelihood of that happening? 3) What are the consequences?* This definition will be used in this paper. Meanwhile, *safety* is defined as 'a state where the risk has been reduced to a level that is as low as reasonably practicable (ALARP) and where the remaining risk is generally accepted' (Rausand and Haugen, 2020). Hence, safety is a function of risk.

Risk information can be provided through the monitoring of *risk influencing factors* (RIFs). Øien (2001b) defined a RIF as 'an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity'. In this paper, the general definition by Rausand and Haugen (2020) will be used: *'Risk influencing factors are background factors that influence the causes and/or the development of an accident'*. According to this understanding, RIFs may be used both in qualitative and quantitative models.

Several risk influence frameworks have been developed during the past decades, as reviewed by Yang et al. (2017). They can be made using updated accident and hazardous event data; alternatively, they can be made using predefined sets based on historic accident data, statistics, expert opinions, safety management systems, accident investigation reports, risk assessments, organisation theories, and human performance/reliability analyses, or a mix of several of these. Accident models are frequently used to identify factors influencing an unwanted occurrence (Kjellen and Albrechtsen, 2017).

The RIFs may, and ideally should, belong to several categories covering all relevant risk-influencing information during an operation or at a production plant. In the 1990s, organisational factors were integrated into risk analyses, in addition to technical factors and human errors (Øien, 2001a). In the development of the barrier and operational risk analysis method (BORA), five RIF groups were explored: human, task-related, technical, administrative, and organisational (Aven et al., 2006; Sklet et al., 2006). Yang et al. (2017) identified different factors influencing technical and human safety performance, and grouped them as shown in Table 1.

2.3. Safety indicators and approaches

Indicators are measurable operational variables that describe the *condition* of the RIFs (Øien et al., 2011a). There are two types of indicators: risk indicators for use in quantitative risk models (Øien, 2001b; Haugen et al., 2011) and safety indicators (Øien et al., 2011b).

Safety indicators are identified based on sources other than risk models, e.g., incident-based approaches, and are used to measure past, present, and future safety levels (Øien et al., 2011a). Safety performance indicators are also used to measure the accident risk control performance in enterprises (Kjellen and Albrechtsen, 2017). In this paper, we use fish escape data to identify risk factors, but do not establish a quantitative risk model; therefore, the operational variables developed here will be referred to as *safety indicators*.

Safety indicators may be used to measure safety performance related to different elements of the workplace system, including personal, technical, and organisational safety (Kongsvik et al., 2018). In addition, human and operational safety indicators should be included to catch the

Table 1
Categories of risk influencing factors (RIFs) for technical and human safety performance, as presented in the review by Yang et al. (2017).

RIF group	Description
Indirect organisational	Root causes for system risk/accidents. E.g., safety culture, risk management, human resource management.
Direct organisational	Organisational factors affecting the performance of the workers. E.g., training, communication.
Operational management	Support functions for scheduling and structuring the team's work during an operation. Overlaps partly with direct organisational RIFs. E.g., work practice, procedures, planning.
Personal/individual level	Individual characteristics of an operator. E.g., competence, knowledge, workload.
Task characteristics	Characteristics of the activity itself. E.g., methodology, complexity, time pressure.
Technical system	Factors affecting the condition of the equipment, technical systems, or their components. E.g., material properties, human-machine interface (HMI), maintainability.
Environment	Physical environmental factors which may affect the performance of both humans and technical systems. E.g., weather conditions.

risk influencing factors emerging from the activity itself (Yang et al., 2017).

Safety indicators are often divided into leading and lagging safety indicators, although the difference between them in practice has been contested (Hale, 2009; Hopkins, 2009; Wreathall, 2009; Øien et al., 2011a). Leading safety indicators measure the risk control performance and the factors contributing to unwanted occurrences, while lagging indicators measure the consequences of incidents in terms of losses (Kongsvik et al., 2018). The terms *proactive* (leading) and *reactive* (lagging) safety indicators are also used (Øien et al., 2011b). Kjellen and Albrechtsen (2017) present another approach, categorising safety indicators according to the three main parts of an accident analysis framework: 1) indicators derived from causal factors (contributing factors and root causes of the accident); 2) indicators related to process safety performance (aspects of the accident sequence); and 3) loss-based indicators (measures of injuries, substance leaks, structural failures).

The UK Health and Safety Executive (HSE, 2006) have based their proposed safety indicator programme on a small number of critical risk control systems, or barriers, as illustrated in the Swiss cheese model by Reason (1997). The method emphasises the importance of a *dual assurance* approach. This means that for each risk control system, or safety barrier, there is one lagging indicator for the outcome of the process, and one associated leading indicator that is used to measure the success of the control activity. The idea is that these twin sets of indicators provide the safety management system with updated information on the safety performance of the activity itself (active) and on the outcome of the activity (reactive). Hence, dual assurance should be considered when the indicators are related to safety barriers.

Safety indicators have been implemented in aviation and in the chemical processing, nuclear power, and petroleum industries to monitor safety performance (Øien et al., 2011b). An example is the Risk Level project (RNNP) for Norwegian oil and gas industry (PSA Norway, 2019). The aim is to control health, safety and work environment risks for personnel during offshore installations (Vinnem et al., 2006). The first study was conducted in 2001, and after that, annual analyses of barrier performance and of technical and personal safety have been performed. Questionnaires and interviews are conducted every second year to assess the safety climate, which supplements the quantitative indicators in RNNP. A study has shown that safety climate parameters are significantly correlated with gas leaks (Vinnem et al., 2010). This study documents the importance of investigating human and organisational factors as contributing root causes for major accidents and for occupational accidents.

There are four main approaches to developing safety indicators (Øien et al., 2011b):

1. Using safety performance as a basis (e.g., number of hazardous events, barrier failures, deviations, errors, compliance with safety regulations). See, e.g., HSE (2006), Kongsvik et al. (2010), Holmen et al. (2017b).
2. Deriving risk indicators from quantitative risk assessments and risk models; e.g., Øien (2001b), Haugen et al. (2011), Vinnem et al. (2012).
3. Implementing the incident-based or retrospective approach through accident investigation methods; e.g., Leveson (2015), Kjellen and Albrechtsen (2017), Holen and Utne (2018), Yousefi and Rodriguez Hernandez (2020).
4. Applying resilience theories (Øien et al., 2010; Thieme and Utne, 2017).

The strategy should be chosen based on the intended use of the indicators, the quality and extent of the available data, and appropriate quality criteria (see the next section). In this paper, a combination of strategies 2 and 3 was used. The identification of hazards and chains of events was based on a national database of aggregated accident report data; i.e., the analysis was incident-based (strategy 3). Information on contributing conditions and causes was extracted from the database and illustrated using a qualitative Bayesian network (BN) approach, which is a modification of strategy 2. The causal analyses on human, technical, and organisational contributing factors, suggest multiple cascading chains of events. This approach captures and systematises a range of causal chains, which can be used to identify risk influencing factors and subsequently derive safety indicators. It is based on learning from multiple incidents, and is therefore suitable for developing safety indicators on an industry level. The original strategy 2, to develop a risk model, would imply a simplification of the real-world complex causalities found in the data, and important RIFs might hence be hidden.

2.4. Quality criteria for safety indicators

Several suggestions for evaluation criteria can be found in the literature on safety indicator development. Five examples are presented in Table 2. The SMART principle, which stands for specific, measurable, achievable, relevant, and time-related, was originally developed to formulate objectives for general management (Doran et al., 1981). Kjellen and Albrechtsen (2017) focus on safety (performance) indicators for feedback control, and have adopted the criteria suggested by Tarrants (1980): 1) Observable and quantifiable; 2) Valid indicator for the risk of loss; 3) Sensitive to change; 4) Compatible; 5) Transparent and easily understood; and 6) Robust against manipulation.

These criteria duplicate the SMART principle to a large extent, except for *sensitive to change* and *robust to manipulation.* It is important for proactive indicators to give early signs of a deteriorating safety level, e.g., during operations or during a production process. Furthermore, if the indicator is used by the management to, for example, release bonuses, the workers and local managers might be tempted to manipulate the data or discourage incident reporting (Kjellen and Albrechtsen, 2017).

Haugen et al. (2011) looked into criteria suggested for risk and safety indicator development in the oil and gas sector and chose the following: validity, quantifiable, regular monitoring, and sensitivity to change. Holen and Utne (2018) also addressed indicator quality through questions in their framework for fish farming based on the 'System Theoretic Process Analysis' (Leveson, 2015): 1) Is the indicator data already collected, or can it be collected? 2) Is the safety relevance of the indicator understandable/agreed upon by the end users? 3) Is the indicator objectively measurable? 4) Is the indicator robust against manipulation?

3. Method

3.1. Development of safety indicators

The approach in this paper is a modification of the method developed by Haugen et al. (2011). Accumulated incident-based data and risk analyses are used to illustrate chains of events in a qualitative BN, which are then used to identify risk influencing factors and develop safety indicators. (For more on BN, see, e.g., Rausand and Haugen (2020)). This procedure is a combination of strategies 2 and 3 from Section 2.3. The risk model in strategy 2 is replaced with a qualitative BN, and the nodes in the BN consist of causal factors and conditions extracted from accident report data (strategy 3). The influences between the nodes are determined from accident and risk analyses. The approach can be used to map the factors that influence risk based on several aspects: risk for fish escape, occupational accidents, environmental risk, risk to material assets, and food safety.

The steps of the method are as follows:

1. Identify the causes of the type of accident to be examined. Using the available accident reports, identify the environmental, technical, operational, and organisational conditions, and the hazardous events that affect the risk level.
2. Which work operations are the events connected to? Identify the operations of high risk.
3. Define/draw a Bayesian network for the accident to illustrate causal chains. All conditions/events are illustrated with individual nodes, and the influence between them is illustrated with directed arcs.
4. Identify the risk influencing factors (RIFs) for each condition/event contributing to the accident.
5. Identify safety indicators to measure the condition of each RIF, and specify the states for the indicator.
6. Evaluate the safety indicators according to the chosen quality criteria.

Section 4 describes the steps in more detail as applied to the case of farmed fish escapes.

3.2. Data collection

The method is used with the undesirable event of escape of fish. This application was selected because the authorities had pointed this out as one of the two main challenges in the fish farming industry (Ministry of Trade and Fisheries, 2015), and a national strategy has been launched to meet this challenge (Ministry of Trade and Fisheries, 2017b). Fish escapes have been the subject of accident investigations at a national level, both by the authorities and by researchers (Directorate of Fisheries, 2020; Thorvaldsen et al., 2015; Føre and Thorvaldsen, 2021).

Table 2
Safety indicator criteria retrieved from scientific literature.

Reference	Doran et al. (1981)	Haugen et al. (2011)	Leveson (2015)	Kjellen and Albrechtsen (2017) (Tarrants, 1980)	Holen and Utne (2018)
Criteria	Specific	Validity	Complete	Observable and quantifiable	Data exist or may be collected
	Measurable	Quantifiable	Consistent	Valid indicator for the risk of loss	Relevance understood and agreed upon
	Achievable	Regular monitoring	Effective	Sensitive to change	Objectively measurable
	Relevant	Sensitivity to change	Traceable	Compatible	Robust against manipulation
	Time-related		Minimal	Transparent and easily understood	Unbiased
			Continually improving	Robust against manipulation	

In Norway, fish escape incidents must be reported to the Directorate of Fisheries, who analyse the reports according to number of fish lost, the type of fish farm, the operational and technical contributing causes, and the sea and weather conditions at the time of the incident. The aim is to assess the regulations and develop recommendations for the industry regarding mitigating measures, as well as to identify focus areas for the Directorate's risk-based inspections in the fish farming industry.

This study uses data from the original reports submitted by the fish farm companies, gathered in a worksheet for further internal analysis. The Directorate has provided access to the aggregated fish escape report data from the years 2010–2016, as well as to the original accident reports. In this material, the Directorate have used the following categories for the coarse sorting of the fish escapes: external cause, operational cause, structural cause, unsolved cause, not relevant.

The identified RIFs and proposed safety indicators in our study were discussed in detail with three operational managers in three Norwegian fish farming companies. We noted their expert judgement to use as input for steps 5 and 6 of the method. Operational managers are the local general managers, and are responsible for quality and safety in their workplaces. One of the operational managers consulted in this study worked on a service vessel, and was responsible for the vessel and for the crew performing specialised servicing and maintenance operations at the regional fish farms owned by the company. The other two operational managers worked at salmon farms, and were responsible for personnel, daily tasks, fish welfare, and maintenance operations during the production cycle. Each consultant had more than 10 years' experience in the fish farming industry.

4. Results

This chapter summarises the results from applying the methodology on fish escape. To develop a complete list of RIFs at a fish farm, the method should also be applied to fish health and welfare, safety and health of the workers, the external environment, material assets, and food safety, but that is beyond the scope of this paper.

The results are summarised and presented in Appendix 1, which will be referred to several times in the following sections.

4.1. Step 1 – Identify the causes of the accident

The accident to be examined is the escape of farmed salmon and trout from Norwegian fish farms. A systematic analysis of confirmed escapes from Norwegian fish farms during the years 2010–2016 shows that the main direct causes for salmon and trout escape are a hole in net, a submerged net, leakage from tubs, and loss of fish during transport (to and from fish farms, hatcheries, and processing plants) (Føre and Thorvaldsen, 2017). During these years, there were 218 fish escape events, with a total of 1,770,000 escaped salmon and trout. The most common direct causes of escapes are defects in the main barrier, the net cage. In 102 events, when 76% of the fish escaped, it was through a *hole in the net*. The number two direct cause, *submerged net,* occurred in 13 incidents (16% of the escaped fish). Number three was leakage from tubs on land facilities (smolt production or similar), which caused 15 of the incidents (7% of the escaped fish). Loss of fish during transport happened 44 times; however, only a small number of fish escaped in each event, accounting altogether for 1% of the total escapees.

In brief, during the years 2010–2016, more than half of the incidents and 92% of the escaped fish were caused by a defect in the main physical barrier, such as a hole in the net or a submerged net cage. These two types of events are related to essential production and maintenance activities at the fish farm. It was therefore decided to further limit the study in this paper to these two hazardous events.

4.2. Step 2 – Describe the work operations of high risk

Previous studies identify specific fish farm operations with increased risk of fish escape (Jensen et al., 2010; Sandberg et al., 2012; Thorvaldsen et al., 2015). These are crane operations, operations with well-boats moored to the fish cage, and operations on the net cage structures when crowding fish, which means reducing the volume of the cage by lifting the bottom weight system attached to the net cage. Their common characteristic is strong forces being used either on or near the net cage with its attached structures and moorings. The operations were analysed in depth during a workshop, confirming that the operations are considered critical by the fish farm and service vessel workers when it comes to risk for both fish escape and personnel safety (Holmen et al., 2017a).

Using the escape reports provided by the Directorate of Fisheries, we extracted the information on the type of operation performed before or during the fish escape. This had not been documented for every incident; however, there was enough information to link every operation to a chain of events (see next section, step 3). The main operations identified were *well-boat operations, fish crowding, delousing with a tarpaulin, net cleaning, net replacement, daily operations,* and *service operations*. Furthermore, these operations also involve work tasks that are connected to the hazardous events. These are *mort collection equipment handling, bottom weight handling, handling of the float line, vessel mooring,* and *net repair*. Some of these work tasks, e.g., vessel mooring, are involved in several of the main operations. Handling of the float line is a crucial step in the fish crowding operation. Net repair is a frequent task in service operations, and failures during this task has been reported as a cause of a hole in the net leading to fish escape.

4.3. Step 3 – Develop a Bayesian network for the accident

The BN illustrates the influence of the contributing causes on the hazardous events from step 2, and is used to identify RIFs and safety indicators. The visualisation of the chain of events is used to capture contributing causes that might not be evident to the managers or to the operator at the sharp end. Fig. 2 shows the resulting BN based on the contributing causes of the hazardous events *a hole in net* and *a submerged net* as recorded in the fish escape reports. The available causal analyses of these incidents were used as inputs to describe the chain of events, and to clarify the hazards, failures, and conditions to be included as nodes in the network (Føre and Thorvaldsen, 2017; Thorvaldsen et al., 2015; Thorvaldsen et al., 2018; Holmen et al., 2017a). In addition, environmental conditions that influenced the risk levels in the registered events were identified, i.e., bad weather, waves, wind, water currents, fog, precipitation, darkness, flotsam, and predators.

The layout of the network has been chosen to show the connections between the main operations (parent nodes to the left), important work tasks, indirect causes and conditions, and the direct causes leading to the failure of the net barrier (hole in net or submerged net). The intermediate nodes/influencing conditions were sorted into environmental, organisational, operational, and technical categories, and these are shown in different colours in Fig. 2. The BN is not quantifiable, as the purpose is to identify relations between the risk factors for use in safety indicator development. Table 3 summarises the underlying factors (hazards, failures, and conditions) identified for the main causal chains.

4.4. Step 4 – Identify risk influencing factors (RIFs)

The contributing causes, failures, and other conditions in the causal chains illustrated in the BN were generalised into a set of risk influencing factors (RIFs). The RIFs were formulated so as to represent the nodes in Fig. 2. According to the definition in Section 2.2, these RIFs are different aspects or conditions of the fish farm material assets, production facilities, organisation, and operations, which influence the development of the hazardous events *a hole in the net* and *a submerged net*. Table 4 shows the resulting 31 RIFs, are classified according to the four categories introduced in step 3: environmental, organisational, operational, and technical.

Fig. 2. Graphical illustration (BN) of causal chains for escape of farmed fish caused by a hole in the net or a submerged net.

Table 3
The most frequent underlying factors contributing to the hazardous events a hole in net and a submerged net (cf. Fig. 2).

Work operation	Organisational condition	Operational failure	Technical failure	Environmental impact	Hazardous event
Daily operations	Inadequate inspection and maintenance	–	Electrical failure Fire damage to floater	–	Submerged net
Well boat operation	Procedure violation	Vessel collision	–	Darkness	Submerged net
Net replacement	Procedure violation Insufficient training	Insufficient knotting	–	Bad weather	Submerged net
Bottom weight handling	Work pressure Procedure violation Insufficient training Inadequate inspection and maintenance Inadequate risk assessment	Faulty mounting of gear or component	Chafe or tear from bottom weight/rope	Bad weather	Hole in net
Service operation	Inadequate inspection and maintenance Inadequate user manual and documentation	Faulty mounting of gear or component	Chafe or tear from bottom weight/rope	Bad weather	Hole in net
Mort collection system handling	Procedure violation Inadequate inspection and maintenance Inadequate risk assessment	Faulty mounting of gear or component Crowding net stuck	Mort collection system chafe or tear	Bad weather	Hole in net

The climate parameters (bad weather, high waves, strong wind and water currents, darkness) are the first conditions to be considered before an operation starts, and the environmental category therefore represents important RIFs. Wind and rough sea conditions have a significant impact on the complexity of the operations and the severity of the possible undesirable events (Bjelland et al., 2015). The phrase *bad weather* is often used in daily speech and when reporting accidents, but it cannot be quantified, and is therefore not in itself useful as a risk factor. Bad weather is an undesirable combination of wind, waves, and visibility, and rain or snow and low temperatures may cause icing. In addition, the external factors of flotsam and predators are reported to cause holes in the nets.

Four organisational RIFs were identified from the six nodes in Fig. 2 (the text from the nodes in brackets): Workload (work pressure), work practice (procedure violation; inadequate inspection and maintenance), competence (insufficient training), procedures and documentation (inadequate risk assessment; inadequate user manual and documentation). The terminology used for the organisational RIFs is consistent with previous studies on organisational factors (Kongsvik et al., 2010).

Seven operational RIFs were derived from the failures in operations that are recurring events in the causal chains, increasing the risk of fish escape. An additional operational RIF (fish pump mounting) was derived from a technical failure node, *fish pump chafe or tear*, because the causal analysis showed that incorrect fish pump mounting has caused net chafing. The technical RIFs are derived from the failures and hazardous events linked to or caused by mounted equipment, technical structures, and net cage components. Monitoring the state of these RIFs is critical for the technical condition of the fish farm.

Table 4
Overview of RIFs for the hazardous events a hole in net and a submerged net.

Environmental RIFs	Organisational RIFs	Operational RIFs	Technical RIFs
Wind	Workload	Vessel manoeuvring at the fish farm	Electric power supply condition
Water current	Work practice	Vessel manoeuvring alongside the net cage	Floater condition
Waves	Competence	Net attachment procedure	Feed barge mooring
Visibility	Procedures and documentation	Component/equipment installation	Floater biofouling degree
Icing		Crowding net handling	Anchor placement
Flotsam		Net hook storage	Mort collection system condition
Predators		Net cage repair service	Component/equipment technical state
		Fish pump mounting	Mooring line condition
			Coupling plate/crowfoot placement
			Sinker tube chain state
			Sinker tube placement
			Bottom weight system condition

4.5. Step 5 – Develop safety indicators for measuring RIFs

4.5.1. Safety indicator development

The RIFs are not always directly quantifiable, and safety indicators are therefore introduced in this step to measure the condition of each RIF (cf. Section 2.3). The safety indicators should reflect changes in the associated RIFs with respect to how often the condition might change during a production cycle or an operation. For example, the environmental RIF *water current* needs to be subdivided into the indicators *water current speed* and *water current direction*, which can both be measured continuously with sensors. Another example is the organisational RIF *workload*. To measure the state of *workload*, four safety indicators are suggested in Appendix 1. One of these is the fraction calculated as *workers available* divided by *workers needed*. The output of the suggested safety indicators are numbers that may be recorded from day to day, and could be used by the management to monitor possible changes in the condition of the RIF *workload* over time.

Appendix 1 lists the RIFs and the safety indicators suggested for each RIF for the hazardous events *a hole in net* and *a submerged net:* ten safety indicators for monitoring environmental RIFs, 11 for organisational, eight for operational, and 12 for technical (41 safety indicators altogether).

4.5.2. Indicator update frequencies, measuring methods, and states

Update frequencies of the indicators, proposed methods for measurement, and estimated values for acceptable/unacceptable indicator states are also included in the proposed methodological approach. The suggestions are based on a literature survey of studies on occupational and operational risks (e.g., (Holmen et al., 2018, Thorvaldsen et al., 2020) and regulatory requirements (e.g., the Working Environment Act, Aquaculture Act, technical standard NS 9415). Initial suggestions were adjusted after discussions with operational managers based on the managers' practical experience and company internal procedures, if applicable. The final recommendations are presented in Appendix 1.

The update frequency for an indicator is based on how often the condition of the RIF changes, and it needs to be considered in relation to the available measuring method. It may not be possible, nor desirable, to acquire continuous updates. If the measuring method is manual – for example, based on checking weather forecasts – the update frequency is limited to updating the forecast.

Safety indicators representing frequently changing RIFs may be monitored continuously or logged at intervals (e.g., using sensors or automatic systems), while more slowly changing RIFs can be assessed qualitatively by questionnaires, inspections, or audits (Kongsvik et al., 2010). For some RIFs, different safety indicators may enable different measurement approaches. An example is the RIF *work practice*. Three safety indicators are suggested to measure the condition of this RIF, with different methods for measurement. One is to use the number of registered procedure nonconformities per year as the indicator. Another is to conduct a yearly audit and check whether the operators describe a work practice consistent with the documented procedure. The third safety indicator could be to check the backlog on safety critical maintenance, ideally weekly, or at least before forecasted storms.

4.6. Step 6 – Evaluate safety indicators

Section 2.4 presents indicator quality criteria extracted from previous safety indicator studies. An indicator programme in the fish farming industry requires resources and attention from the organisation, and the output should be worthwhile. The workers also need to understand the importance of updating the safety management system with the necessary data. Hence, the indicators should reflect measurable changes in RIFs. To keep the workers motivated, the management should offer feedback showing that the data has been received and processed according to the shared safety objectives. Follow-up of the indicators should not conflict with other more important objectives, such as daily routines to ensure fish welfare and growth. The indicators should ideally use documentation and data already being collected, or complement existing data collection. This information is essential in corporate safety management systems to prevent undesirable events (Kjellen and Albrechtsen, 2017). Based on these considerations, as well as on the literature survey on indicator quality criteria (Section 2.4), the following criteria were chosen:

1) Observable
2) Quantifiable
3) Relevance understood and agreed upon
4) Robust against manipulation.

The interviews with the three operational managers provided additional input for the evaluation. The information on how and how often the safety indicators can be updated, as well as on the acceptable/unacceptable states, was used to evaluate the indicators according to the quality criteria 1 and 2 (observable and quantifiable). All indicators fulfilled these criteria.

Criterion 3, relevance understood and agreed upon, was also tested during the interviews. One of the suggested operational safety indicators, *number of undesirable vessel contacts with net per month*, did not pass this test, as this is fortunately a rare incident. Hence, 40 of the suggested safety indicators represent true RIFs for fish farming operations.

By contrast, criterion 4, *robust against manipulation*, was not fulfilled for 28 of the 41 suggested indicators. This reflects the proposed measuring method for these safety indicators, which depends on subjective actions by an operator. The indicators may therefore be easily manipulated, either intentionally or accidentally. However, if the inspections were conducted by an external inspector, the indicator measurement would be robust against manipulation. Therefore, none of the indicators were refuted based on this criterion. This is further discussed in Section 5.1.3.

The results of the evaluation for each criterion are included in Appendix 1. The scores are marked *yes* (criterion fulfilled) or *no* (not fulfilled). Altogether, 40 safety indicators were accepted based on the quality criteria.

4.7. Example of a safety indicator programme: fish crowding

Although this paper is limited to fish escape incidents, there are many safety indicators involved. The selection of indicators needs to be adapted to the operation being planned. This section demonstrates this with the example of the fish crowding operation.

The operation of fish crowding is one of the most high-risk operations for fish escape, as identified in step 2 (Section 4.2). Fig. 3 shows the causal chain for this operation only, with the other operations and nodes removed from the BN from Fig. 2.

The process of fish crowding consists of several tasks. The purpose is to gather the fish in a smaller volume and prepare for fish treatment or delivery. The first task is to remove the mort collection system and other mounted equipment attached to the net cage. Several events of *a hole in the net* have occurred due to the mort collection system tearing the net wall. The underlying causes are mounting failures or damaged metal components.

The next task is to reduce the volume of the net cage by lifting the bottom weight and the stretching system (sinker tube and chains) using a vessel crane. Repeated iterations are performed around the cage, lifting the sinker tube one step at the time. This is a safety-critical task, according to the fish escape reports. If a part of the net gets stuck in one of the vertical ropes, or if a sinker tube component is damaged, this might tear a hole in the net. Furthermore, when the net volume is sufficiently reduced (the net is 'lined up'), a crowding net is used to gather some of the fish now being crowded close to the surface. During fish transfer to a well-boat, a float line is used to reduce the diameter of the net gradually and to move the fish close to the fish pump inlet. These tasks are also associated with hazardous events described in the fish escape reports.

The safety indicator programme for *reducing the risk of fish escape during fish crowding* is shown in Fig. 4. It was prepared by applying the method to fish escape incidents (described in Sections 4.1 to 4.6, and summarised in Appendix 1). The stages of the fish crowding operation were defined according to the practice in the fish farming industry: *operational planning*; *start and execution of the operation*; and *follow-up*. Table 5 shows the relation between the nodes of the causal chains in Fig. 3, the RIFs and their associated safety indicators (Fig. 4). See the list of RIFs and safety indicators in Appendix 1 for suggested update frequencies, methods for measurement, and indicator states.

The current practice is to plan the operation one week in advance (personal communication with operational managers). The weather forecast needs to be checked regarding wind speed and direction, which also determines wave conditions. The lunar phase is also important, because it determines the tidal currents, i.e., water current speed and direction. The proportion of available/needed personnel should also ideally be checked, along with the proportion of operators with the required qualifications and the risk assessment documentation. Furthermore, if there is any maintenance backlog, or a detected failure in the mort collection system, this will increase the risk of fish escape during the crowding of the fish.

Before starting, the number of overtime hours per operator in the previous shift should be checked, to be prepared in case the workers are at the limit of their allowed overtime hours. This will also indicate whether the crew are rested or not. At low temperatures, structures should be checked for icing. The wind, water current, wave conditions, and visibility distance should be monitored throughout the operation. During the follow-up after the operation, the stretching system components (sinker tube chain, sinker tube placement, bottom weight) should be inspected after the net cage has been released to its full volume. The net cage components and the mounted equipment inside the net cage should also be inspected after they had been manipulated or reattached.

5. Discussion

5.1. Methodological approach

The aim of the study was to develop a method for identifying safety indicators for operations in the fish farming industry based on accessible data and accident analyses. At present, no such systematic monitoring of indicators related to operational safety has been implemented. The method is based on a combination of the risk-model-based and incident-based strategies (cf. Section 2.3). This approach was chosen because a national registry of reported data from multiple fish escape incidents was available. This data, together with previous accident analyses, was used to generate the BN in Fig. 2. The approach is further discussed in

Fig. 3. Causal chain for the operation fish crowding.

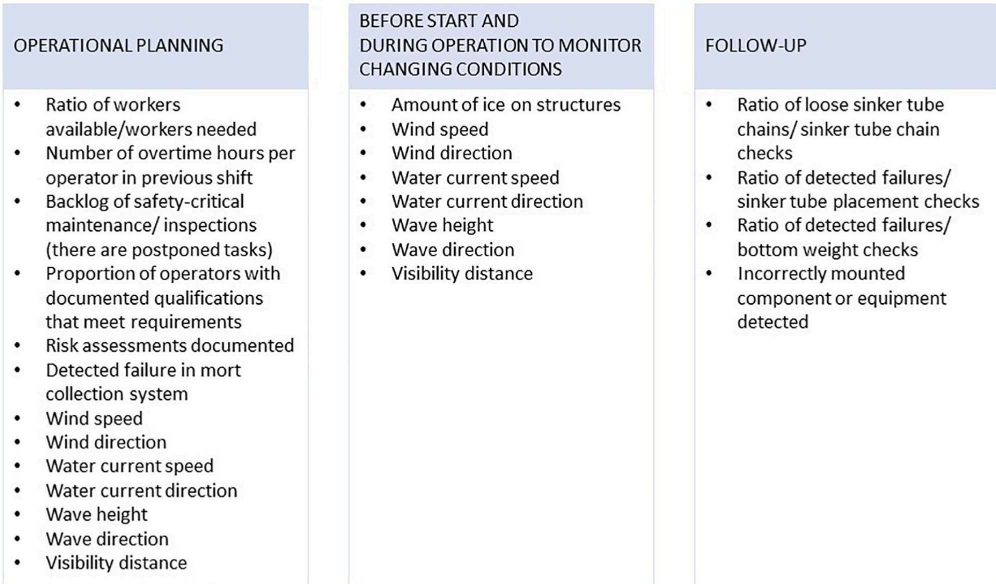

Fig. 4. Suggested safety indicator programme for fish escape during fish crowding.

the following sections.

5.1.1. Accident reports as the data source

Both confirmed and suspected fish escapes must be reported to the Norwegian Directorate of Fisheries using a standardised form. The quality of the reports may vary considerably in terms of how detailed and comprehensive the written description of the incident is. The reports may also be biased. Some of the reported incidents are investigated by the authorities to gather more detailed information about the incident, which may be used to prosecute the company. Data accumulated over several years is made available for research purposes, and provides a good insight into direct and indirect causes of escapes. The focus in the original accident reports is primarily on technical and operational failures. For additional information on human, organisational, and technical causes, this study has relied on previous analyses of fish escapes in Norway (Thorvaldsen et al., 2015; Føre and Thorvaldsen, 2017; Thorvaldsen et al., 2018). Furthermore, operational managers from fish farms were also involved in the final assessment of the RIFs and safety indicators. The combination of data sources used in this study is good quality.

The method proposed in this paper is generic and could also be used for occupational accident data. The Norwegian Labour Inspection Agency collects data on serious occupational injuries, which can be used to identify safety indicators for occupational risk influencing factors. The aquaculture production regulations also require fish farmers to report data to the Food Safety Authority (Ministry of Trade and Fisheries, 2018), which could be used to develop safety indicators for fish health and welfare. Similar databases are available for vessel and maritime occupational accidents (Norwegian Maritime Authority) and environmental pollutants (Norwegian Environment Agency).

Section 2.3 presents different strategies for identifying safety indicators, some of which use data from accidents as input, together with other available risk information. Holen and Utne (2018) developed safety indicators for occupational accidents in the fish farming industry, based on operational scenarios and analyses of control actions. Their approach seems to be a good strategy for developing safety indicators in fish farming if little or no accident data is available. The involvement of experienced operators and other experts is needed to describe the operations and control structures in detail.

Another alternative source of information on causal chains of hazardous events are risk assessments, combined with thorough descriptions of operational procedures. Risk assessments are mandatory for fish farm operations, but a previous study showed that they are not always performed in accordance with the requirements (Holmen et al., 2018). To improve the quality of the information and ensure that all relevant hazards are included, Yang et al. (2020b) developed a method for identifying hazards in aquaculture operations based on established hazard identification methods. The evaluation criteria require that the method should be 1) easy to use and easily convertible to a set of checklists; 2) able to identify hazards that could impact personnel, the environment, fish welfare, and marine assets; 3) able to reduce risks associated with hazards unknown to the operators; 4) able to identify the interactions of the various parties involved in the operation; and 5) able to reduce adverse effects of inexperienced risk analyst. The method requires good insight into the work, and has the advantage that it covers all risk dimensions of a fish farm operation. It could thus be used to identify additional hazards and contributing causes that are not covered in accident or nonconformity reports.

A potential challenge is that the method might reflect what the investigators expect to find, and hence not be truly objective (Lundberg et al., 2009). Another concern is that if the authorities require accidents reports, as with fish escape incidents in Norway, the reports will contain information given by whoever had filled the accident report form. These reports could of course also be biased or incomplete. However, several years' worth of accident reports should still be representative of the most common types of events and failures, and should capture the most probable causal chains.

5.1.2. Qualitative networks to illustrate causal chains

BNs remain little used in safety research for the aquaculture industry. A qualitative BN was included for three main reasons. First, the BN method is a quick and illustrative way of sorting accident analysis data into causal chains for safety indicator development. If new causal factors are identified in later risk assessments or accident investigations, new

Table 5
The relation between the underlying factors and conditions contributing to the hazardous event hole in net during fish crowding (nodes in Fig. 3), the relevant RIFs, and the associated safety indicators (Fig. 4).

Node in Fig. 3	Risk influencing factor (RIF)	Safety indicators in Fig. 4
Environmental impact		
Bad weather	Undesirable combinations of low temperatures, wind, current, waves and precipitation	Expressed by individual indicators, se below
	Icing	Amount of ice on structures
Strong wind	Wind	Wind speed Wind direction
Strong current	Water current	Water current speed Water current direction
High waves	Waves	Wave height Wave direction
Darkness	Visibility	Visibility distance
Organisational condition		
Work pressure	Workload	Ratio of workers available/ workers needed Number of overtime hours per operator in previous shift Number of overtime hours per operator during a rotation Proportion of operators reporting that the workload often/very often is too high
Procedure violation	Work practice	Number of registered procedure nonconformities per year (per work operation) Proportion of operators describing a work practice equal to the documented procedure
Inadequate inspection and maintenance	Work practice	Backlog on safety-critical maintenance/inspections (there are postponed tasks)
Insufficient training	Competence	Proportion of operators with documented qualifications that meet requirements
Inadequate risk assessment	Procedures and documentation	Risk assessments documented
Inadequate user manual and documentation	Procedures and documentation	Number of registered failures due to inadequate manual Updated documentation for critical equipment and main components
Operational failure		
Faulty mounting of gear or components	Component/equipment installation	Incorrectly mounted component or equipment detected
Crowding net stuck	Crowding net handling	Crowding net gets stuck during the operation
Net hook lost inside net cage	Net hook storage	Lost net hook inside net cage during fish crowding
Technical failure		
Equipment chafe or tear	Component/equipment technical state	Ratio of detected failures/ component checks
Mort collection system chafe or tear	Mort collection system condition	Detected failure in mort collection system
Component chafe, tear or aging	Component/equipment technical state	Ratio of detected failures/ component checks
Loose sinker tube chain	Sinker tube chain state	Ratio of loose sinker tube chains/ sinker tube chain checks
Sinker tube contact	Sinker tube placement	Ratio of detected failures/ sinker tube placement checks
Chafe or tear from bottom weight/ rope	Bottom weight system condition	Ratio of detected failures/ bottom weight checks

nodes can be added. Second, the structure is logical, and even complex dependencies between contributing factors can be displayed as a part of the network. This is necessary for selecting the proper safety indicators for each RIF. The BN is easily accessible to the users of the safety indicators, as well as to other stakeholders. Third, the visual presentation is easy to understand for practitioners and may therefore also be used in the fish farm industry for communication about accident causalities, training, risk assessments, procedure improvements, and more. The BN can also be a supplement in documenting operational risk management.

The method for developing safety indicators suggested in this paper requires insight in the characteristics of technological installations, marine operations, and organisation of the fish farm production. It is suitable for establishing qualitative risk models at the industry level because it is based on accident data gathered at a national level. The causal chains in the model are not weighted, but available analyses show which contributing causes are most frequent and should therefore be prioritised.

The operational RIFs in this study are derived from failures in operations that are recurring in the chain of events, resulting in fish escape. They could be defined as human errors/failures; however, for the risk management in this industry, it is not beneficial to focus on the individual operator because of the complex sociotechnical system. Furthermore, the contributing causes are many and interconnected, and deliberate violations are rare. Insufficient risk assessments, lack of training, and high workloads are the underlying factors that might result in unintentional procedure violations. The organisational RIFs should be assessed with appropriate methods, such as the operational safety condition (OSC) method (cf. Section 6.1.). A previous study has already evaluated the use of the OSC method for identifying organisational risk influencing factors in fish farming (Holmen et al., 2017b). The study concluded that the organisational factors presented in the work by Kongsvik et al. (2010) also apply to fish farm operations.

Since we have had access to first-hand accident report data, another possible strategy would be to use an accident investigation approach, such as the accident model by Kjellen and Albrechtsen (2017). This model consists of three parts: input, process, and output. These may be used to identify RIFs and derive related safety indicators. Our work combines information from accident reports and facilitates the exploration of the causal factors influencing the risk of the accident (input side), but also considers the risks during the operation (process). The output is the consequences. The advantage of the BN model over the accident model approach is that it allows for graphic illustration of the complex influence between the factors. Several of these share contributing causes, but the analysis of the reported accidents rarely shows identical causal chains. This insight is needed for developing preventive actions and targeted safety barriers.

In the future, data might become available that would transform the qualitative network into a quantitative risk model. Calculating and identifying reliable probabilities for the conditional probability tables (CPT) in a quantitative BN requires data that is not yet available for the fish farming industry on an aggregated level. This would require the frequencies and descriptions of all marine operations done at fish farms over the years, both successful and not, as well as accurate wave, water current and wind recordings from the site, the number of personnel, their competence levels, the technical condition of structures, and more.

Novel machine learning techniques may be used to compensate for the lack of data. A recent study by Yang et al. (2020a) presents a risk model that uses multi-source data and machine learning processes guided by major risk influencing factors to define operational limits for fish farm operations. Although not validated yet, the model is promising as a decision-making tool for fish farms. Monitoring of certain safety indicators could also provide an additional source of data for validating such a model.

5.1.3. Quality criteria for indicator properties

Four quality criteria were selected for the safety indicators:

observable, *quantifiable*, *relevance understood and agreed upon*, and *robust against manipulation*. The ratings *yes* and *no* in Appendix 1 are based on the input from the operational managers. The safety indicators in Appendix 1 meet the three of the criteria, except the indicator *number of undesirable vessel contacts with net per month*. The industry consultants did not find this indicator relevant, and could not remember when this last happened. It has been reported as an undesirable event causing a hole in the net at some point in the past, but the data includes only the years 2010–2016, so barriers may already have been implemented, reducing the likelihood of this event.

The criterion *robust against manipulation* needs further explanation. The basic assessment is whether the recorded indicator value or state may be manipulated by the operator: is it possible to report a wrong value deliberately? Or does the measurement depend on subjective assessments? Four out of ten environmental safety indicators were rated *no* on this criterion (visibility distance, amount of ice on structures, flotsam, and presence of predators). These indicators are measured by visual inspection, which is a subjective assessment. It is of course not in the interest of the operator to deliberately report a wrong value, but a predator may not be detected due to bad eyesight, or one operator's tolerance for the amount of ice may be greater than another's. For such indicators, objective measurement methods should be preferred whenever possible.

Altogether 28 out of 40 safety indicators were also rated *no* for *robust against manipulation*. This criterion might be considered unnecessary, as the safety indicators have not been disqualified if they did not meet it. In fact, since the indicators were found relevant for other reasons, their lack of robustness should alert the managers to put extra effort into ensuring the reliability in measuring these indicators. Appendix 1 shows that no operational or technical safety indicator is considered robust, as they all depend on visual inspection or subjective reporting. Again, it is not in the operator's interest to manipulate the result in the long run; however, a shortcut might be taken for other reasons. The root cause for this is most likely among the organisational RIFs.

In contrast, two of the indicators for workload, *number of overtime hours per operator in previous shift* and *number of overtime hours per operator during a rotation* are considered robust. It is in the operator's interest to get paid for these hours, so there is a control mechanism assuring that the manager does not manipulate the data to, for example, hide that the workers had not had their breaks as required by regulations. It should be emphasised that the problem is rather that the operators work too long shifts, and the safety indicators are highly relevant, since failures occur more frequently when the workers are tired (Thorvaldsen et al., 2020).

To establish a safety indicator set for an operation, the additional criterion of a *minimum set of indicators* is recommended (Seljelid et al., 2012; Leveson, 2015). In our study, the criterion of relevance corresponds to the minimum set in that the indicators must not be overlapping or too numerous; i.e., all safety indicators included must be associated only with necessary preventive actions. Furthermore, the method favours indicators fulfilling this criterion, because the BN nodes are a result of already sorted and merged overlapping/repeating conditions and events extracted from the data sources. However, the size of the indicator set should still be considered in the end to minimise the time needed to update the indicator states so as to not add too much to the operational manager's workload. It could also be a wise strategy to implement a smaller indicator programme first, and expand it after the routine is established.

The BN design in Fig. 2 represents the accident (fish escape) as the consequence of hazardous events in a network of causal chains. The number of documented fish escapes (accidents) and the number of detected holes in the net and of submerged nets would be the lagging indicators in this terminology. The safety indicators in Appendix 1 are thus all leading indicators. This is as expected, since the aim of the study is to develop indicators that can help prevent escape.

5.2. Practical use of safety indicators

The current risk management practices concerning the production and marine operations at the Norwegian fish farms are supervised by five authorities, as described by Holmen et al. (2018). The regulatory requirements specify a few safety indicators at national level, such as the number of escaped fish or of occupational injuries (cf. Background, Section 1.1). The follow-up of regulatory requirements on risk management is perceived as tedious and fragmented work. The new approach presented in this study could support the required risk management activities within the different regulatory areas, and tie them together in a holistic system. It may also be used to prioritise the order of inspection and maintenance tasks which are decided by the fish farm manager. It provides relevant safety indicators, which to a large extent can be measured using readily available data, and can help prevent undesirable events that might develop into a fish escape accident. This study has focused on the example of fish escape; however, the approach would also apply in the cases of risk to fish welfare or risk of occupational injury.

The safety indicators may be a decision support tool for the operational manager, or they may be used to monitor the trend at both the company level and the national industry level. At company level, a negative trend of the indicators associated to the RIFs "workload" and "work practice" would indicate a need for additional, or better qualified, workers to assist in the safety-critical operations. A need for improving technical standards in the company would be documented by a negative trend in the technical indicators.

The safety indicators could be of high interest to the top management level to benchmark each company nationally in areas of common interest like prevention of fish escape or reduction of occupational risk. This would also allow the authorities evaluate the effect of regulatory requirements or identify a need for implementing new framework conditions. The introduction of the Norwegian technical standard NS 9415 (Standard Norway, 2009) was a measure to reduce the number of escapes due to technological failures and breakdown of fish farms. It has improved the technical condition of the Norwegian fish farms significantly, as documented by the escape numbers after the implementation (Jensen et al., 2010).

The safety indicators and the BN model could help fish farm workers understand how they contribute to safety. The safety indicators should be used in planning the work, both in the short and the longer term, particularly when the scheduled operation is associated with an increased risk for fish escape. E.g., before fish crowding operations, it should be checked if the operators have the required training, and that the technical condition of the net and the attached component are satisfactory to reduce the risk for tearing holes. During the operation, undesirable changes in the indicator values should trigger mitigating actions immediately.

Some RIFs are obvious to an experienced operator, but it may be less obvious which ones to prioritise when the workload is high or when an incident occurs. The causal chains derived from the BN in Fig. 2 show which RIFs should take priority in operational risk management, and may be used for operator training purposes and risk assessment updates. Several of the reported incidents are the result of chafing between components under water, which may not be discovered until later. The complex marine operations and structures, combined with the responsibility for living fish, require a level of judgement that might be gained after several years of training. However, the implementation of new technology would require additional competence. A safety indicator programme could therefore be a quality-assuring tool for both new and experienced fish farm managers.

According to Leveson (2015), general safety indicators cannot be established because systems are different from one another. This is partly supported by our approach. The BN in Fig. 2 can be seen as an illustration of several causal chains (systems) that shows how they interconnect in the fish escape scenario. The causal chains start with the operation performed, and a set of safety indicators can be associated with the contributing conditions, hazards, and events (RIFs) in each chain. For fish farming, this is the recommended approach, because safety indicators and checklists need to be developed for the specific work being performed. A production cycle at a fish farm lasts approximately 18 months and involves a wide variety of operations, from refilling fodder silos, inspection, and maintenance of technical structures, to caring for the living fish. An effective risk management system, therefore, needs to be broken down into manageable pieces, where the smallest component could be a safety indicator programme for an operation or a maintenance checklist for critical components.

The interviews with the fish farm operational managers revealed that some of the RIFs are already included in daily inspection and maintenance programmes at the fish farms, although they are not discussed in terms of safety indicators with defined states. Every day, except for days of 'bad weather' and gales, the operators spend several hours doing the daily round of each net cage. Every attachment point of the net cage is checked (at one farm, 12 attachment points per net cage). The condition of the floater, lice skirt, feeding system, and other equipment inside or attached to the net cage is checked visually. The mort is collected, using either a landing net or a mort pump (if installed). Components of the mooring system that can be seen from the water surface are also inspected. Furthermore, the daily inspection also includes cleaner fish feeding, removal of seaweed, and general housekeeping, as well as observing the behaviour of the farmed fish. The daily round thus covers three technical RIFs: *floater condition*, *mort collection system condition* (if lifted to the surface), and *the technical state of components/equipment that can be reached or seen from the gangway or work vessel*. Furthermore, the daily round includes the environmental RIFs of *icing*, *predators*, and *flotsam*, and the operational RIF of *net attachment*.

The maintenance intervals of the equipment, structures, and components are currently determined by the technical certification requirements, and not by risk assessments. The causal chains show that some critical components need to be checked more often if the influencing conditions increase the risk levels. To reduce the risk of escapes, safety indicators should be implemented with update frequencies based on the accepted risk level. An example is the interval for checking moorings and coupling plates, which, according to the regulations, should be checked yearly. Daily visual inspections are supposed to reveal structural failures, and to a large extent they do, at least when done by an experienced operator. On the other hand, everything cannot be seen from the deck of a vessel alongside the fish cage, and the weather and/or the visibility might be insufficient to perform the daily check properly. Based on the causal chains, it seems advisable to do an extra check after periods of bad weather, i.e., combinations high wind speed, waves, and strong water currents, to detect any possible contact between structural components or equipment and the net cage so as to prevent chafing or tearing.

The qualitative BN in this paper has been designed based on factors identified from the escape reports. It may be expanded by including all known preventive safety measures (barriers) that reduce the probability of an escape, both regulatory and other. Barrier functions that reduce the scale of the fish escape accident may also be shown (these would constitute the mitigation of consequences). In some cases, these measures might be the same as those that reduce the likelihood of the event. Thus, the qualitative BN model in this paper can be developed further into a comprehensive illustration of risk factors and preventive and mitigating actions to be used for raising awareness among operators and doing risk assessments at fish farms.

6. Conclusions

Preventing fish escape is one of the major safety challenges in the Norwegian fish farming industry, and reporting escaped fish is mandatory. Safety indicators are a useful tool for risk management of fish farming operations and for learning from undesirable events. This study has used qualitative BNs to describe events, conditions, and causal chains from fish escape accident report data to develop safety indicators. The suggested method is generic and may be applied to other types of accidents.

Environmental, organisational, operational, and technical RIFs were identified from a qualitative BN illustrating the causal chains. To measure the state of each RIF, safety indicators were identified and evaluated according to four quality criteria: *observable*, *quantifiable*, *relevant*, and *robust against manipulation*. This resulted in 40 safety indicators associated with 31 RIFs for fish escape. The assessment concluded that the indicator set is of good quality. For a specific operation, a subset of relevant indicators should be implemented. The example of fish crowding has been presented, where 26 safety indicators are implemented in the operational stages of planning the operation, at the start of and during activities, and during the follow-up after the operation.

Safety indicator programmes would provide the fish farm industry with a systematic tool to monitor the safety levels of operations associated with a high risk of fish escape. Some of the technical RIFs are to some extent already included in maintenance and inspection programmes. However, the results suggest that the intervals should be revised according to other RIFs present, such as environmental or organisational RIFs, that are known to influence the risk of the hazardous events. The RIFs and safety indicators may also be used to supplement safety management; in internal audits and quality improvement work; to develop preventive measures; and in training of fish farm personnel. The BN model could be extended to include barriers and mitigating actions, as this would increase the effectiveness of the illustrations of causal chains needed in risk assessment and for training purposes.

6.1. Future needs and research

At present, Norwegian authorities are encouraging innovation in new fish farm production concepts by granting so-called development permits for free to novel designs that require considerable investments (Directorate of Fisheries, 2018). The motivation is to enable fish farming at more exposed locations to increase marine food production (Fredheim and Reve, 2018). The permits are licences that allow companies to increase their fish production based on certain criteria for technology advancement. One important criterion is that the design must not resemble previous designs by the same or other companies. Consequently, the complexity of aquaculture technology increases, and the need for systems that monitor technical and operational safety is growing.

A couple of decades ago, the Technical Condition Safety method (TTS) was implemented in a Norwegian oil and gas company as a tool to review technical safety systems and safety barriers in maintenance, inspection, and design of offshore production systems (Ingvarson and Strom, 2009). Adapting and applying the TTS method to monitor the performance of safety barriers in fish farming operations is also a promising strategy, which requires a joint effort from companies to develop a TTS framework for the fish farming industry. In the present BN approach, technical risk factors were identified, which could be used to highlight the critical safety barriers of the fish farm structures.

A thorough evaluation of long-term changing RIFs, such as the organisational and operational conditions, requires audits involving all managerial levels of the organisation, as well as the sharp-end workers. The operational safety condition method, OSC (Kongsvik et al., 2010), has been evaluated as a supplement for auditing organisational RIFs in fish farming (Holmen et al., 2017b). Based on feedback from industry representatives, OSC is too resource-demanding to be used in its original form (Andreassen and Olsen, 2019). A better approach could be to develop a standardised OSC programme for specific accident scenarios in fish farming; for example, establish questionnaires to gather data systematically, and use checklists for document analyses and work practice assessments.

Further work should also study barrier functions to manage the most important risk factors, including environmental, organisational, operational, and technical RIFs. This would provide an additional approach to preventing hazardous events and to developing and implementing targeted risk-reducing measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Summary of the results from steps 4–6 of the proposed method. Risk influencing factors (RIFs) have been derived from the fish escape reports (step 4); associated safety indicators were identified to measure the condition of each RIF (step 5); and the safety indicators were evaluated according to the quality criteria (step 6). The table also includes the frequency of change, the proposed measurement method, and the possible states for each indicator.

Risk influencing factor (RIF) (step 4)	Safety indicator (step 5)	Indicator update frequency	Proposed method for measurement	Evaluation quality criteria (step 6)				States and suggested mitigating actions of selected indicators
				Observable	Quantifiable	Relevant	Robust	
Environmental RIF								
Wind	Wind speed	Continuously	Weather forecast, sensor	Yes	Yes	Yes	Yes	State 1[a] – Acceptable to start/continue operation State 2 – Operation can be started/continued with extra precautions State 3 – Not acceptable to start/continue operation
	Wind direction	Continuously	Weather forecast, sensor	Yes	Yes	Yes	Yes	As above
Water current	Water current speed	Continuously	Lunar phase, sensor	Yes	Yes	Yes	Yes	As above
	Water current direction	Continuously	Lunar phase, sensor	Yes	Yes	Yes	Yes	As above
Waves	Wave height	Continuously	Weather forecast, sensor	Yes	Yes	Yes	Yes	As above
	Wave direction	Continuously	Weather forecast, sensor	Yes	Yes	Yes	Yes	As above
Visibility	Visibility distance	Hourly	Weather forecast, visual inspection	Yes	Yes	Yes	No	As above
Icing	Amount of ice on structures	Daily during winter season	Weather forecast, visual inspection	Yes	Yes	Yes	Yes	No ice – Acceptable to start/continue operation Ice layer on decks, gangways and railings – Operation can be started/continued with extra precautions Heavy ice load, submerged floater – Not acceptable to start/continue operation
Flotsam	Flotsam presence	After storm	Visual inspection	Yes	Yes	Yes	No	Not present Present – Remove, check for damage
Predators	Predator presence	Daily	Visual inspection	Yes	Yes	Yes	No	Not present Present – Remove, check for damage
Organisational RIF								
Workload	Ratio of workers available/workers needed	Weekly Daily during busy periods (e.g., fish treatment, fish delivery)	Assess workers available versus amount of work tasks	Yes	Yes	Yes	No	≥100% – Excellent 75–100% – Acceptable to start/proceed with extra precautions <75% – Not acceptable to start/proceed
	Number of overtime hours per operator in previous shift	Daily during busy periods	Check registered overtime	Yes	Yes	Yes	Yes	0 – Excellent 1–5 – Acceptable to continue with extra precautions >5 – Not acceptable to continue. Allow operators to rest
	Number of overtime hours per operator during a rotation	Monthly	Check registered overtime	Yes	Yes	Yes	Yes	0 – Excellent 1–10 – Acceptable to continue with extra precautions

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Risk influencing factor (RIF) (step 4)	Safety indicator (step 5)	Indicator update frequency	Proposed method for measurement	Evaluation quality criteria (step 6)				States and suggested mitigating actions of selected indicators
				Obser-vable	Quanti-fiable	Rele-vant	Robust	
								>10 – Not acceptable to continue. Allow operators to rest
	Proportion of operators reporting that the workload often/very often is too high	Yearly	Questionnaire or audit	Yes	Yes	Yes	No	0% – Excellent 0–20% – Acceptable. Improve staffing plans for busy periods and reduce overtime >20% – Not acceptable. Increase permanent staffing
Work practice	Number of registered procedure nonconformities per year (per work operation)	Yearly	Check nonconformity registry	Yes	Yes	Yes	No	0 – Excellent 1–2 – Acceptable. Review procedures with operators and observe operators >2 – Not acceptable. Retrain operators
	Proportion of operators describing a work practice corresponding to the documented procedure	Yearly	Audit	Yes	Yes	Yes	Yes, if objective inspector	100% – Excellent 90–100% – Acceptable. Review procedure with operators and observe operators <90% Not acceptable. Retrain operators
	Backlog of safety-critical maintenance/inspections (there are postponed tasks)	Weekly and before forecasted storms	Check maintenance log	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable Immediate corrective action needed. Review procedure
Competence	Proportion of operators with documented qualifications that meet requirements	Before every safety-critical operation	Check HR system	Yes	Yes	Yes	Yes	100% – Excellent 75–100% – Acceptable. Operation can be started with extra precautions < 75% – Not acceptable. Operation cannot start
Procedures and documentation	Risk assessments documented	Yearly Check content before safety-critical operation	Document inspection Audit	Yes	Yes	Yes	Yes	Yes – Excellent No – Not acceptable. Operations critical for fish welfare can be started with a preceding SJA. Risk assessments should be documented before next operation.
	Number of registered failures due to inadequate user manual	Every 6 months	Check nonconformity registry Audit	Yes	Yes	Yes	No	0 – Excellent 1–2 – Acceptable. Review procedures with operators and continue. Give feedback to manufacturer to update manual. >2 – Not acceptable. Stop operation and retrain operators with manufacturer present for update of manual.
	Updated documentation for critical equipment and main components	Every 6 months	Document inspection Audit	Yes	Yes	Yes	Yes	Yes – Excellent No – Not acceptable. Obtain manual/documentation
Operational RIF								
Vessel manoeuvring around fish farm	Number of undesirable vessel contacts with critical fish farm structures per month	Monthly	Check nonconformity registry Check vessel log	Yes	Yes	Yes	No	0 – Excellent <0–1> – Deviation. Review procedure with personnel ≥1 – Not acceptable. Review procedure and retrain vessel crew
Vessel manoeuvring alongside net cage	Number of undesirable vessel contacts with net per month	Monthly	Check nonconformity registry Check vessel log	Yes	Yes	No	No	Not applicable
Net attachment procedure	Missing knots detected	After installation	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Review procedure with personnel
Component/equipment installation	Incorrectly mounted component or equipment detected	After installation/on removal	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Review procedure with personnel
Crowding net handling	Crowding net gets stuck during the operation	Each fish crowding operation	Check nonconformity registry	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Check

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Risk influencing factor (RIF) (step 4)	Safety indicator (step 5)	Indicator update frequency	Proposed method for measurement	Evaluation quality criteria (step 6)				States and suggested mitigating actions of selected indicators
				Obser-vable	Quanti-fiable	Rele-vant	Robust	
								for holes in net and review procedure
Net hook storage	Lost net hook inside net cage during fish crowding	Each fish crowding operation	Check nonconformity registry	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Stop operation and remove net hook. Review procedure with personnel
Net cage repair service	Faulty net repairs detected during a production cycle	Every production cycle	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable Review inspection procedure. Check certificate/service card
Fish pump mounting	Faulty fish pump mountings detected during or after fish transfer	After mounting, before fish transfer starts	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Review procedure with personnel
Technical RIF								
Electric power supply condition	Detected failure in electric power supply	Daily	Sensor, visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Immediate corrective action needed
Floater condition	Defective floater elements detected	Daily	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Immediate repairs needed. Revise inspection interval
Feed barge mooring	Barge mooring failure detected	As required[b]	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Immediate corrective action needed. Revise inspection interval
Floater biofouling degree	Heavily biofouled floaters detected at fish farm	As required[b]	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Biofouling removal needed. Revise inspection interval
Mort collection system condition	Detected failure in mort collection system	After handling of the mort collection system and before removal	Visual inspection	Yes	Yes	Yes	No	No – Excellent Yes – Not acceptable. Corrective maintenance needed. Revise inspection interval
Anchor placement	Ratio of detected anchor displacements/anchor checks	As required[b] (Recommended: after storms)	Visual inspection	Yes	Yes	Yes	No	0 – Excellent <0–1> – Deviation. Corrective maintenance needed. Revise interval for routine maintenance ≥1 – Not acceptable. Corrective maintenance needed. Revise inspection procedure
Component/ equipment technical state	Ratio of detected failures/component checks	As required[b]	Visual inspection	Yes	Yes	Yes	No	As above
Mooring line condition	Ratio of detected failures/mooring line checks	As required[b]	Visual inspection	Yes	Yes	Yes	No	As above
Coupling plate/ crowfoot placement	Ratio of detected failures/coupling plate/ crowfoot checks	As required[b]	Visual inspection	Yes	Yes	Yes	No	As above
Sinker tube chain state	Ratio of loose sinker tube chains/sinker tube chain checks	As required[b] (Recommended: after operations involving moving the stretching system)	Visual inspection	Yes	Yes	Yes	No	As above
Sinker tube placement	Ratio of detected failures/sinker tube placement checks	As required[b]	Visual inspection	Yes	Yes	Yes	No	As above
Bottom weight system condition	Ratio of detected failures/bottom weight checks	As required[b]	Visual inspection	Yes	Yes	Yes	No	As above

[a] States of environmental indicators must be set according to the local conditions, type of operation, equipment used, etc.
[b] NS 9415 requires that the recommended maintenance/inspection interval be set by the manufacturer and described in the mandatory user handbook.

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IMT-2003-1	Chen, Haibo, MK	Probabilistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation. (Dr.Ing. Thesis)
IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
IMT-2003-3	Chezhian, Muthu	Three-Dimensional Analysis of Slamming. (Dr.Ing. Thesis)
IMT-2003-4	Buhaug, Øyvind	Deposit Formation on Cylinder Liner Surfaces in Medium Speed Engines. (Dr.Ing. Thesis)
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IMT-2004-8	Soma, Torkel	Blue-Chip or Sub-Standard. A data interrogation approach of identity safety characteristics of shipping organization. (Dr.Ing. Thesis)
IMT-2004-9	Ersdal, Svein	An experimental study of hydrodynamic forces on cylinders and cables in near axial flow. (Dr.Ing. Thesis)
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		Situations at Sea. (Dr.Ing. Thesis)
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IMT-2005-13	Heggernes, Kjetil	Flow around marine structures. (Dr.Ing. Thesis
IMT-2005-14	Fouques, Sebastien	Lagrangian Modelling of Ocean Surface Waves and Synthetic Aperture Radar Wave Measurements. (Dr.Ing. Thesis)
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IMT-2006-19	Reite, Karl Johan	Modelling and Control of Trawl Systems. (Dr.Ing. Thesis)
IMT-2006-20	Smogeli, Øyvind Notland	Control of Marine Propellers. From Normal to Extreme Conditions. (Dr.Ing. Thesis)
IMT-2007-21	Storhaug, Gaute	Experimental Investigation of Wave Induced Vibrations and Their Effect on the Fatigue Loading of Ships. (Dr.Ing. Thesis)
IMT-2007-22	Sun, Hui	A Boundary Element Method Applied to Strongly Nonlinear Wave-Body Interaction Problems. (PhD Thesis, CeSOS)
IMT-2007-23	Rustad, Anne Marthine	Modelling and Control of Top Tensioned Risers. (PhD Thesis, CeSOS)
IMT-2007-24	Johansen, Vegar	Modelling flexible slender system for real-time simulations and control applications
IMT-2007-25	Wroldsen, Anders Sunde	Modelling and control of tensegrity structures. (PhD Thesis, CeSOS)
IMT-2007-26	Aronsen, Kristoffer Høye	An experimental investigation of in-line and combined inline and cross flow vortex induced vibrations. (Dr. avhandling, IMT)
IMT-2007-27	Gao, Zhen	Stochastic Response Analysis of Mooring Systems with Emphasis on Frequency-domain Analysis of Fatigue due to Wide-band Response Processes

		(PhD Thesis, CeSOS)
IMT-2007-28	Thorstensen, Tom Anders	Lifetime Profit Modelling of Ageing Systems Utilizing Information about Technical Condition. (Dr.ing. thesis, IMT)
IMT-2008-29	Refsnes, Jon Erling Gorset	Nonlinear Model-Based Control of Slender Body AUVs (PhD Thesis, IMT)
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IMT-2008-31	Ye, Naiquan	Fatigue Assessment of Aluminium Welded Box-stiffener Joints in Ships (Dr.ing. thesis, IMT)
IMT-2008-32	Radan, Damir	Integrated Control of Marine Electrical Power Systems. (PhD-Thesis, IMT)
IMT-2008-33	Thomassen, Paul	Methods for Dynamic Response Analysis and Fatigue Life Estimation of Floating Fish Cages. (Dr.ing. thesis, IMT)
IMT-2008-34	Pákozdi, Csaba	A Smoothed Particle Hydrodynamics Study of Two-dimensional Nonlinear Sloshing in Rectangular Tanks. (Dr.ing.thesis, IMT/ CeSOS)
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IMT-2008-36	Drummen, Ingo	Experimental and Numerical Investigation of Nonlinear Wave-Induced Load Effects in Containerships considering Hydroelasticity. (PhD thesis, CeSOS)
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IMT-2008-39	Alsos, Hagbart S.	Ship Grounding. Analysis of Ductile Fracture, Bottom Damage and Hull Girder Response. (PhD-thesis, IMT)
IMT-2008-40	Graczyk, Mateusz	Experimental Investigation of Sloshing Loading and Load Effects in Membrane LNG Tanks Subjected to Random Excitation. (PhD-thesis, CeSOS)
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IMT-2008-42	Ruth, Eivind	Propulsion control and thrust allocation on marine vessels. (PhD thesis, CeSOS)

IMT-2008-43	Nystad, Bent Helge	Technical Condition Indexes and Remaining Useful Life of Aggregated Systems. PhD thesis, IMT
IMT-2008-44	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
IMT-2009-45	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
IMT-2009-46	Pedersen, Tom Arne	Bond Graph Modelling of Marine Power Systems. PhD Thesis, IMT
IMT-2009-47	Kristiansen, Trygve	Two-Dimensional Numerical and Experimental Studies of Piston-Mode Resonance. PhD-Thesis, CeSOS
IMT-2009-48	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT
IMT-2009-49	Hong, Lin	Simplified Analysis and Design of Ships subjected to Collision and Grounding. PhD-thesis, IMT
IMT-2009-50	Koushan, Kamran	Vortex Induced Vibrations of Free Span Pipelines, PhD thesis, IMT
IMT-2009-51	Korsvik, Jarl Eirik	Heuristic Methods for Ship Routing and Scheduling. PhD-thesis, IMT
IMT-2009-52	Lee, Jihoon	Experimental Investigation and Numerical in Analyzing the Ocean Current Displacement of Longlines. Ph.d.-Thesis, IMT.
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IMT 2009-57	Kong, Xiangjun	A Numerical Study of a Damaged Ship in Beam Sea Waves. Ph.d.-thesis, IMT/CeSOS.
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IMT 2010-62	Shao, Yanlin	Numerical Potential-Flow Studies on Weakly-Nonlinear Wave-Body Interactions with/without Small Forward Speed, Ph.d.thesis,CeSOS.
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IMT 2010-66	Jia, Huirong	Structural Analysis of Intect and Damaged Ships in a Collission Risk Analysis Perspective. Ph.d.thesis CeSoS.
IMT 2010-67	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
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IMT-2012-89	Zhu, Suji	Investigation of Wave-Induced Nonlinear Load Effects in Open Ships considering Hull Girder Vibrations in Bending and Torsion, CeSOS

IMT-2012-90	Zhou, Li	Numerical and Experimental Investigation of Station-keeping in Level Ice, CeSOS
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IMT-18-2018	Christoph Alexander Thieme	Risk Analysis and Modelling of Autonomous Marine Systems
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IMT-18-2020	Jone Torsvik	Dynamic Analysis in Design and Operation of Large Floating Offshore Wind Turbine Drivetrains
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