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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

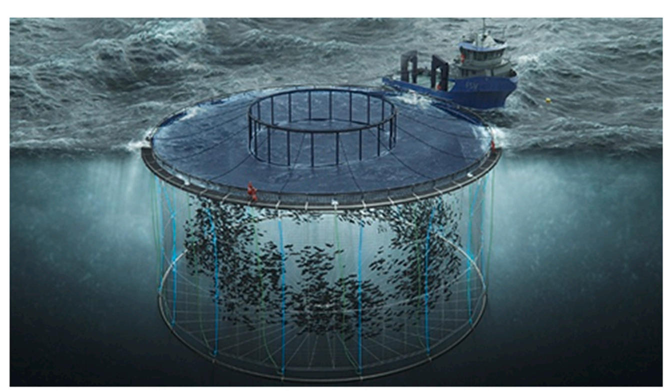

Fig. 1. Illustration of a circular net cage with attached components (permission from Scale AQ).

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

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.

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 Water current Waves Visibility Icing Flotsam Predators	Workload Work practice Competence Procedures and documentation	Vessel manoeuvring at the fish farm Vessel manoeuvring alongside the 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 Anchor placement Mort collection system condition Component/ equipment technical state 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.

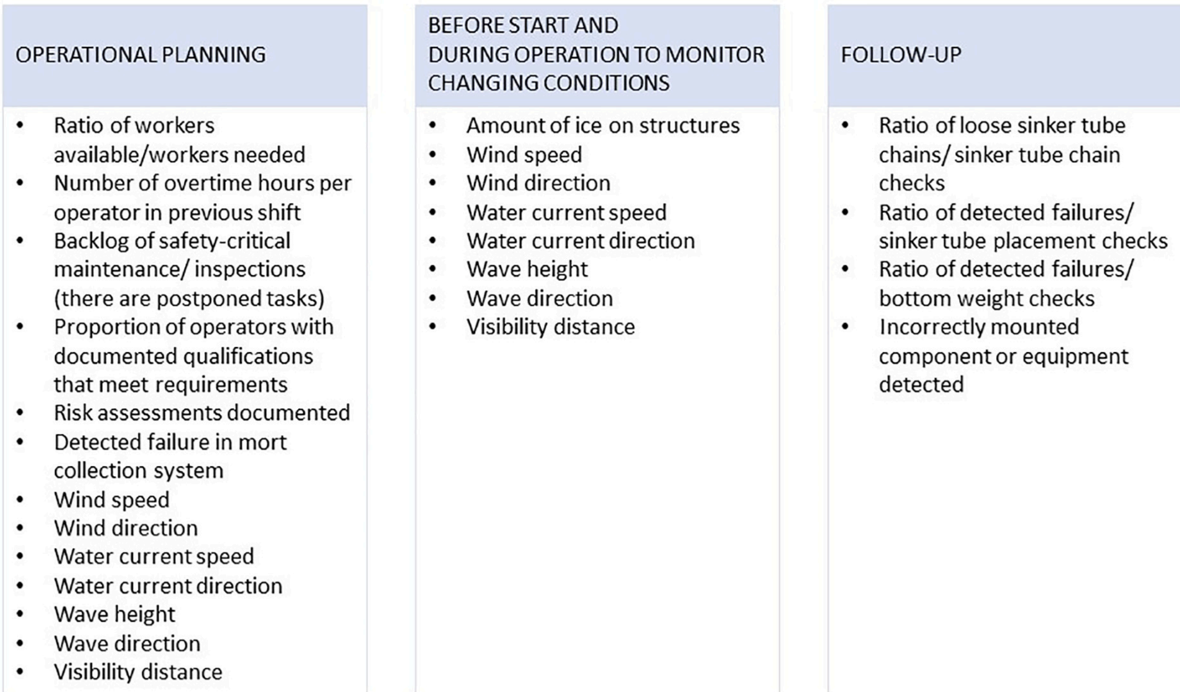

Fig. 4. Suggested safety indicator programme for fish escape during fish crowding.

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
				Obser-vable	Quanti-fiable	Rele-vant	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
				Observable	Quantifiable	Relevant	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
				Observable	Quantifiable	Relevant	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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