Major accidents in Norwegian fish farming

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The Norwegian fish farming industry is experiencing accidents that may have serious consequences for fish-farm operators, the environment, and the farmed fish themselves. Fatalities and serious personnel injuries, mass mortality of fish during and after operations, introgression of genes from farmed salmon, the spread of disease and material damage to assets are among the consequences. The reputation of the industry and the market value of its products may also suffer as a result of such incidents. Other industries have developed regulations aimed at preventing incidents called major accidents, which are usually defined as accidents that have different characteristics than occupational accidents. A holistic and efficient risk management system needs to cover all types of incidents. In spite of serious accidents, regulators have yet to adopt a holistic approach to the prevention of major accidents in Norwegian aquaculture. Here, we describe and discuss five main risk dimensions in the aquaculture industry that provide a holistic view of the complex risk picture of fish farming; fish welfare, personnel safety, risk to the environment, economic loss and food safety. Hazards that emerge in the fish production process and in the local environment, have consequences both for the fish farm and for society as a whole. On the basis of characteristics drawn from definitions of major accident regulations in other industries and the risk dimensions of fish farming, we propose a general definition of major accidents. The definition is discussed based on the type of risks that occur in fish farming, and with an emphasis on accidents that have happened in the Norwegian aquaculture industry. The occurrence of major fish farming accidents shows that a systemic approach to safety and risk management is needed. Regulators and industry are already looking to the offshore petroleum industry in order to develop and adapt technology and risk management for aquaculture. Approaches to risk regulation in the two industries are discussed and some differences pointed out. Barrier management is one of the potentially holistic and systemic major risk management methods required in offshore regulation that is seen as a possible way forward for the fish farming industry, and we offer some reflections on adopting this method to fish farming.

Keywords; Major accident, Fish farming, Risk, Risk management, Safety

1 Introduction

Recent decades have seen a number of accidents in the fish farming industry. Examples are escapes of up to 175 000 fish, delousing operations in which several thousand fish have died both during and after the operation, and serious human injuries and even fatalities (AIBN, 2015; NTB, 2016a; Ramfjord and Honningsvåg, 2012). These accidents obviously have high actual and potential consequences for personnel, fish and the environment. The inherent properties of the industry; keeping live animals at sea in open net cages with limited protection from environmental forces, offers scope for many potentially hazardous scenarios. Fish farm personnel are exposed to high-energy hazards in their work (Holen et al., 2017a), while the fish are exposed to pathogens and sea-borne parasites, and must undergo delousing treatments (Hjeltnes et al., 2018). The environment and wildlife around fish farms are affected by escaped salmon, sea lice and chemical emissions from the farms (Burridge et al., 2010; Jensen et al., 2010). The general public's perception of the industry is affected by the negative consequences of aquaculture (Jackson et al., 2015; Olsen and Osmundsen, 2017). There are therefore several types of potentially serious risks; food safety issues, fish welfare and health issues must all be considered (Yang et al., 2017), in addition to the environmental, material and personnel safety issues also present in other industries.

The dynamic nature of fish farming makes safety and risk management challenging. Rapid changes in weather, the large volumes of the submerged fish farm structures under the sea, and the large quantities of fish per farm add to the complexity as aspects of these factors are difficult to monitor. The challenges facing the industry have led to the rapid introduction of new production methods and technologies, which the authorities often struggle to monitor. In addition, there is much uncertainty in production and research on the industry, for example with regards to knowledge about how pathogens and salmon lice are spread, and the consequences of these on the environment (Grefsrud et al., 2018). The uncertainty in knowledge has led to controversies, as individual stakeholders may interpret the research-based knowledge as support of an argument for a precautionary-based approach, while others interpret it as support for further expansion (Osmundsen et al., 2017).

Risk management is made additionally complex compared to other marine industries such as the offshore petroleum sector, due to the product being live fish. This introduces the important ethical aspect of maintaining the health and welfare of the fish, and in some cases the difficult aspect of balancing the welfare of fish against human safety concerns (Röcklinsberg, 2014; Vonne et al., 2007).

Accidents with catastrophic consequences with regards to fatalities and the environment in other industries have created the need for major accident regulations. In Europe, the Seveso III Directive (Council of the European Communities, 2012) is the latest version of a Directive which was first issued in 1982 after two major chemical accidents occurred, namely Flixborough (UK) in 1974 and Seveso (Italy) in 1976 (Vierendeels et al., 2011). In the offshore oil and gas industry, major accident regulations were the response to catastrophes such as the Alexander Kielland (1980) and Piper Alpha (1988) disasters (Pitblado, 2011). A Directive from the European Union was also developed with regards to safety of offshore oil and gas operations and amending after the 2010 Macondo blowout in the Gulf of Mexico (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011; Council of the European Communities, 2013). Accidents with similar consequences have not been seen in the fish farming industry, mainly because chemicals are not produced or used in a similar way. The industry is therefore not regarded as a major accident industry in the traditional sense. However, the processing industries and offshore oil and gas have developed risk regulations, risk management strategies, technologies and other tools to mitigate major accident risks and these should be explored with a view to adapting them to improve safety in aquaculture.

Risk regulation established for prevention of major accidents in the offshore oil and gas industry is organized in a co-regulatory regime where the government supervises and assists self-regulatory activities by companies (Baram and Lindøe, 2013). Performance-based rules are set in regulations and supported by industry voluntary standards. Central elements of major risk regulation in the petroleum sector are risk acceptance criteria, an obligation to perform risk reduction processes, and a continuous improvement of health, safety and environment (HSE) (Engen et al., 2013). The requirements in this legislation is based on a holistic risk management approach. This concept may be understood as being the coordinated efforts towards managing aspects of risk that needs to be assessed and managed across different levels, units and disciplines in an organisation (PSA, 2018). Holistic risk management may be achieved through systems approaches to safety, which applies concepts such as emergence, hierarchy, communication, and control found in systems thinking theory (Checkland, 1981). The systems approach treats the interacting components of different social and technical hierarchical levels and is thus a promising approach to facilitate holistic risk analysis and subsequent risk management.

The barrier systems management is a central part of risk management in the offshore oil and gas industry as a holistic concept in which the barrier elements include both organisational, operational and technical efforts to realise the functions of the barriers (PSA, 2017c). The PSA defines barriers (2017c) as "Measures that intend either to identify conditions that may lead to errors, hazards and accident situations, preventing the development of a concrete course of events, affect an event sequence in an intended direction, or to limit damage and/or loss". The theoretical background behind barrier management is the energy-barrier perspective (Gibson, 1961; Haddon, 1980), which has been widely applied in offshore oil production platforms, as a result of well-defined, physically confined and stable hazard sources based on technical core of production (Rasmussen, 1994). The underlying assumption is that accidents happen because of the absence or breach of these barriers. The concept of barriers is further extended into the whole scenarios of hydrocarbon emissions, aiming not just to mitigate but indeed to prevent these from taking place.

One of the main issues regarding the regulatory regime of fish farming is its lack of coordination, and subsequently the sometimes competing objectives (Osmundsen et al., 2017). The fish farming authorities are suggesting a coordinating unit and a more holistic regulation, which incorporates both escape prevention and work safety (The Norwegian Directorate of Fisheries and The Norwegian Maritime Authority, 2017). A holistic risk management strategy similar to that employed in other industries is therefore also recommended for the aquaculture industry (Robertsen et al., 2016; Safetec Nordic AS, 2017; SINTEF Ocean AS, 2017). The Norwegian fish farming authorities are already looking to offshore oil and gas for strategies to prevent fish escape based on the barrier management approach (Norwegian Ministry of Trade Industry and Fisheries, 2017). The barrier approach may, however, also be useful for the prevention of other types of major accidents. Hence, a generally accepted definition of major accidents in fish farming is necessary if a holistic approach to barrier management is to be implemented in the industry. A common definition, which includes all risk dimensions of major accidents, may also contribute to an enhanced understanding and a common goal of preventing major accidents, despite the different authorities having separate regulatory responsibilities.

1.1 Objective of paper

There is currently a focus on knowledge transfer from other industries such as the offshore oil and gas to the fish farming industry (Holmen and Thorvaldsen, 2015). Many of the risk-based approaches that have been developed for offshore petroleum are based on prevention of major accidents. There is no established definition of major accidents in the aquaculture industry (Yang et al., 2018), and safety and risk research in this industry have largely focused on occupational safety and prevention of fish escapes. The objective of this paper is to describe the risk factors present in fish farming, and based on these and current definitions from other industries to propose a major accident definition that covers the major risks in the industry. Further, we discuss how major accidents are regulated in the Norwegian offshore oil and gas industry with regards to aspects such as major accident risk management, including barrier management, in terms of their relevance to fish farming. The paper is aimed at authorities, safety managers in aquaculture companies and researchers interested in safety and risk in the sector.

1.2 Limitations

This paper addresses accidents and risks relevant to Norwegian aquaculture, which mostly produces Atlantic salmon, focusing on the ongrowing phase in the sea. The paper mainly discusses the risks present during operations in the current type of production, which dominates the industry today. However, we acknowledge that there is an increasing focus on exposed fish farming in larger and more technologically advanced sea-based facilities where new and different hazards will emerge, though there is very limited public information on these new concepts. Other production phases such as the hatchery and processing facilities on-land will also represent different hazards and risks than the sea-based fish farming discussed in this paper.

Different terms are used to describe similar concepts. Alternative terms for major accidents used in the literature include high impact-low probability accidents (Paltrinieri and Reniers, 2017), process accidents (Hopkins, 2009), and high-visibility accidents (Saleh et al., 2010). In some research, only the term *accident* itself is defined and used in the context of major accidents (Khan and Abbasi, 1999;

Lindberg et al., 2010). We limit the term *major accident* for undesirable events with severe consequences that should be avoided at all reasonable costs in the aquaculture industry. We acknowledge that this term is used in other industries and is thus loaded with associations of certain types of accidents. However, the term *major accident* is neither too concrete nor too vague to be used in the meaning intended in this paper.

In the process industries, the term *major process accidents* is used (Amyotte et al., 2016), in contrast to *minor* occupational accidents (Hopkins, 2009; Rathnayaka et al., 2011). The difference between occupational accidents and major accidents is found in the consequences of the accidents; major accidents have consequences beyond the immediate occupational area and are characterized by harm to many people, valuables and materials, while occupational accidents normally have consequences for only one person (Jørgensen, 2016). The hazards associated with major accidents are typically material release, dispersion and ignition, resulting in a fire or explosion, while for occupational accidents, slips, trips and falls are the most common causes of injuries.

Risk and sustainability management in aquaculture have similarities, and it can be argued that the two should also be integrated (Utne et al., 2017). However, sustainability issues such as depletion of wild fish used in fodder, benthic impacts under fish farms, the use and consequences of copper on nets, and food safety related to environmental toxins have different properties than major accidents. While these issues have serious consequences, they must be managed through long-term governance, often with a global perspective. This paper does not cover these issues, and focuses on the concept of major accidents.

2 The Norwegian fish farming industry

2.1 Production methods

About 1000 fish farms produce salmon along the coast of Norway. The production mode in the ongrowing phase in the sea uses net cages, either suspended from floaters, such as steel platforms, or from individual circular polyethylene collars with installed gangways. Steel cages present various structural challenges (Jensen et al., 2010), and today, production is mostly carried out using plastic collars. Circular collars may also provide better water quality for the fish due to the larger distance between the net cages, and also creates better maneuvering space around the cages for service vessels. These circular collars are typically 90–157 m in circumference and the nets they support are 15–48 m deep. Sites usually have six to 12 net cages and are moored individually to an anchoring grid, which in turn is anchored to the seabed. Fish are transferred by vessels. Fish farms are normally manned by three-four operators, one or two of them working on vessels while the others operators manage feeding from the feeding barge.

Day to day operations on fish farms include feeding, collecting dead fish, maintenance of equipment and inspection of the plastic floats and net cages for damage. Most operations involving fish or cleaning and maintenance of components under water (which of course is most of the fish farm) require heavy machinery such as cranes and winches. These operations are performed from work vessels, which are usually moored to the net cages. This is an unstable work platform, since both net cages and vessels move with the wind, waves and currents. Important operations performed using work vessels include fetching fish from the cage for lice monitoring, and other operations related to maintenance such as tightening underwater moorings.

2.2 Regulations and risk management

An overview of safety relevant regulations for fish farming is provided by Holmen et al. (2018). The regulations for the fish farming industry are fragmented, at least 12 different safety-related regulations are imposed by five different authorities. These five main authorities are the Directorate of Fisheries, the Norwegian Food Safety Authority, Norwegian Maritime Authority, Norwegian Labour Inspection Agency and the County Administration (Holmen et al., 2018).

In the safety related regulations listed in Holmen et al. (2018) three direct requirements for risk assessments are found, related to prevention of escapes and health control of fish and vessel operation (Regulation on the operation of aquaculture production sites, 2008; Regulation on safety management for smaller cargo vessels, passenger vessels, fishing vessels, 2016). Furthermore, the two sets of regulations on internal control in fish farming (Regulation on internal control, 1996; Regulation on internal control to comply with aquaculture legislation, 2004) require that risks related to hazards and problems regulated in aquaculture legislation should be assessed. Internal control is a general regulation for all industries and implies a delegation of the direct control of safety conditions to the companies concerned, and introduces system auditing as the main tool for the regulatory bodies (Hovden, 1998). No directions regarding how risk assessments should be carried out have been given for the internal control requirements (Rausand and Utne, 2009).

The regulators responsible for the different areas of risk and the authorities appear to be fragmented and with sectoral interests in managing the fish farming industry (Solås et al., 2015). The lack of cooperation between regulatory agencies is seen as a challenge (Osmundsen et al., 2017; Robertsen et al., 2016), and a better integrated structure of the authorities is regarded as essential in order to create a strategic plan for aquaculture (Solås et al., 2015). Due to the fragmented regulations, some safety-related issues may fall between regulatory areas. One example is the case of vessels used in fish farming which have been under the jurisdiction of the maritime authority. This has resulted in safety issues related to e.g., escape and diver's safety (regulated by the Directorate of Fisheries and the Work Inspection Authorities) having somewhat fallen in between jurisdictions, even though the vessels are highly involved in operations where such safety issues are present (Norwegian Directorate of Fisheries, 2017; Norwegian Maritime Authority, 2018).

Fish farmers report that they mainly rely on experience, informal coordination and pragmatic problem solving in their decisions (Osmundsen et al., 2017). However, structured management systems are also in place in many aquaculture companies, often as a measure to satisfy requirements in regulations. For example, maintenance management programs, reporting of deviations and risk assessments are in use (Holmen et al., 2017; Thorvaldsen et al., 2015). Moreover, demands for documentation of different work practices are imposed by certifications, that are implemented to satisfy demands for sustainable production by NGOs and retailers (Vormedal, 2017, Nilsen et al., 2018).

The dynamic nature of the aquaculture industry is regarded as positive by employees, as there is never "a dull day" at work. However, unpredictability and uncertainty in operations also involve challenges. Both fish farm management and the operators working at the net-cages are affected by the dynamic physical environment, and many decisions have to be made where complete information is difficult to obtain. The fish farm operators are often left to themselves to make important day-to-day prioritisations and decisions (Størkersen, 2012), e.g., whether operations should be continued under harsh weather conditions.

2.3 Perception by the general public

In a study of how the media present the aquaculture industry, the issues most focused on with regard to the risks of aquaculture were environmental aspects, such as salmon lice and diseases (Olsen and Osmundsen, 2017). The main debate among the general public concerns the consequences of production with regards to escaped salmon and salmon lice, and the main contributors to this debate are sports anglers, journalists, private individuals and NGOs (Osmundsen and Olsen, 2017). Fish welfare has been of less concern than for other animal husbandry (Vonne et al., 2007), and most consumers possess very little knowledge of farmed fish production and welfare issues (Ellingsen et al., 2015). Focus on fish welfare is increasing (Röcklinsberg, 2014), though consumers in Norway are not willing to be the sole payers for fish welfare, as the main responsibility is regarded as lying with the producers and the government (Ellingsen et al., 2015). Food safety is another area of concern among the general public, however less so in Norway than in other countries such as the UK and US (Schlag, 2010).

3 Risk dimensions in Norwegian fish farming

Yang et al. (2017) discuss five risk dimensions of Norwegian fish farming; fish welfare, personnel safety, environmental impact, financial losses, and food safety. In this paper, we have divided two of the categories into separate risk issues which reflect the authorities' focus on risks in the industry: Fish welfare is separated into handling, salmon lice, and pathogens. Environmental risk is separated into escape of salmon, chemical hazards, and pathogens.

The following presentation and description of the risk dimensions aim to capture the values that should be protected while farming fish. This includes both values within the fish farm (personnel, fish, equipment etc.), as well as values outside it (the environment, wild fish, food safety etc.). Fish farms have impacts on their surroundings and *vice versa*, (Figure 1). On a global scale, risk-based methods have traditionally focused on the consequences for the environment (Bondad-Reantaso et al., 2008). Some risk dimensions are also predominantly located within the fish farm, such as operational safety and material damage to equipment.

The focus of this paper is the management of risks related to on-site operations. A plethora of hazards is present in the general production process, and the specific time limited operations (e.g. maintenance or delousing operation) introduce hazards that are somewhat different from the general risk picture on fish farms. Table 1 shows hazards present in operations and the general production processing in relation to each risk dimension. Some hazards are not easily placed in one category or the other, e.g. those hazards that in case of an accident do not immediately lead to serious damage but might subsequently have serious consequences. Whether hazards and accident types fit into a major accident definition is further discussed in Sections 4.2 and 5.1. The following discussion briefly introduces some characteristics of risk dimensions and hazards, as the individual risk dimensions are research topics in their own right. However, the multitude of hazards present in fish farming shows the complexity of the factors that need to be considered in relation to risk management.

Table 1 Hazards in fish farming, related to operations and general production.

Risk dimension	Hazard category	Hazards present mainly in operations	Hazards present in general production
Fish Welfare	Handling	High-temperature treatment, crowding, pumping and transportation in pipes, harsh handling may cause outbreaks of latent disease, and wounds.	N/A
	Pathogens, parasites and other	Exposure from visiting personnel, equipment and vessels (horizontal contamination). Handling may cause wounds which become infected.	Pathogens imported by smolt from other areas (vertical contamination). Oxygen levels, temperature, food access, local outbreaks of algae.
Personnel Safety Environment	Personnel safety	Use of cranes, vessel-net cages interaction, exposure to chemicals.	Long-term ergonomic factors.
Risk to the environment	Genetic introgression	Net tearing from handling.	Net tearing from equipment abrasion.
	Chemicals	Spillage from chemical medicinal treatments	Chemicals in excess feed released
	Pathogens and parasites	Escaped salmon (included salmon louse) salmon louse	Continuous release of pathogens and parasites from fish farms.

		carrying pathogens and parasites, handling of fish	
Financial losses	Material damage and reputation	Damage to equipment and vessels used in operations. Reputational damage related to accidents.	Wear damage to fish farm equipment and components. Reputational damage related to sustainability.
Food safety	Biological hazards	Exposure from visiting personnel, equipment and vessels.	Contaminated feed
	Chemicals	Pesticides, other veterinary drugs	Polychlorinated biphenyls (PCB), dioxins, veterinary drugs in feed, microplastics.

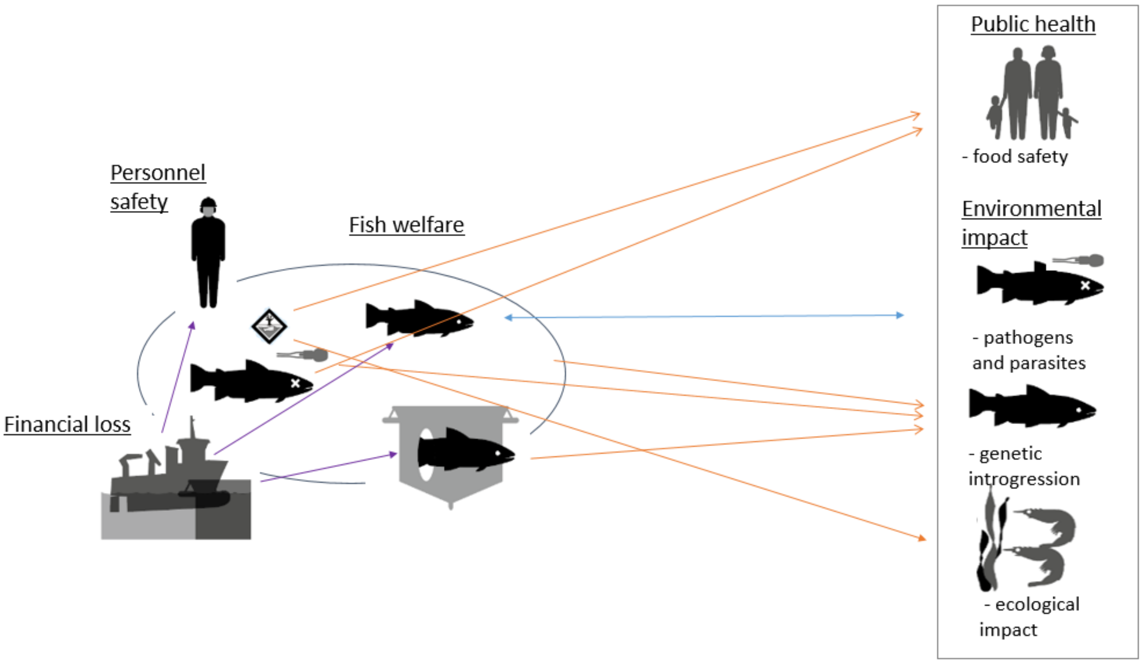

Figure 1: Risk dimensions in fish farming.

3.1 Fish welfare

Handling

Salmon in fish farms are especially liable to suffer reduced welfare during handling, such as crowding and pumping (Erikson et al., 2016; Noble et al., 2018). Handling stresses the fish, and in addition to lower content of oxygen in the water during operations, injuries to gills, skin, fin injuries and snout are common (Noble et al., 2018). Temperature levels, health status and intensity of crowding influences the mortality during handling operations (Noble et al., 2018). Handling is necessary in all operations where fish are being moved to or from the net cage or treated, e.g. in relation to delousing treatments. This has led to increased levels of mortality during and after operations (Grefsrud et al., 2018). Stress or poor water quality may induce disease outbreaks by compromising immune system functions of the fish (Noble et al., 2018).

Pathogens, parasites and other

A wide spectrum of types of viruses, bacteria and parasites is prevalent in the aquaculture industry. An annual survey of fish health is published by the Norwegian Veterinary Institute (Hjeltnes et al., 2018). The World Organization for Animal Health has listed reportable diseases; in Norwegian legislation these are allocated to three classes dependent on whether they are considered national or exotic. (Department of Trade, Industry and Fisheries, 2008). The most common virus disease in class

2 “non-exotic diseases”, is Infectious Salmon Anaemia (ISA) and in class 3 “national diseases”, Pancreatic Disease (PD) (Hjeltnes et al., 2018). PD is a very contagious disease which may lead to elevated levels of mortality, serious damage to muscles and loss of appetite. Outbreaks are often associated with handling in operations (Noble et al., 2018). ISA is a serious contagious disease that leads to causing anemia and internal bleeding. Strict measures, such as control zones around the infected fish farm, are enforced if an infection is identified (Hjeltnes et al., 2018).

Salmon lice infestations involve substantial and costly challenges for the aquaculture sector. Salmon lice are host-specific parasites that have significant physiological and pathological fish welfare consequences as they feed on the skin, mucus and blood of the salmon (Torrissen et al., 2013). High mortality rates have been reported in some areas where infection pressures have not been possible to control (Hjeltnes et al., 2018), and any level of lice infestation will have negative welfare consequences such as stress, loss of appetite and impaired healing of injuries (Noble et al., 2018). There is a higher infestation level in the spring due to higher water temperatures and the return of adult wild salmon from the sea (Torrissen et al., 2013). Due to the strict control and treatment regimes needed to control infestation levels, farmed fish are far more affected by the treatment than the lice infestations themselves (Noble et al., 2018).

3.2 Personnel Safety

Compared to similar industries, injury and fatality rates in the aquaculture industry are high (McGuinness et al., 2013). The accidents with the highest injury potential are related to operations, and typical modes of injuries are impacts, entanglement with gear and falls (Holen et al., 2018a). Fatalities also increasingly occur in relation to operations, as opposed to earlier, when vessel-related fatalities during transport were the main contributor (Holen et al., 2018b). Blows from an object, crushing and man overboard have been the most common causes of fatalities in work operations since 1992. The last tragic incident with multiple fatalities happened in 2012, when a capsize led to two fatalities, due to misuse of a crane under harsh weather conditions (Holen et al., 2018b). Yang et al. (2018) lists some general major hazards relevant for personnel safety at fish farms like; ship on collision course and collision with field related vessels, fires/explosions, diving accidents, structural collapse and breakdown of fish farms.

3.3 Environmental impact

Ecological

The use of chemicals in the fish farming industry has environmental impacts, mainly related to the medical treatment of the salmon, anti-foulings, anaesthetics and disinfectants (Burridge et al., 2010). Chemicals directly released into the sea after delousing treatments may affect crustaceans, seaweed and plankton around the fish farm. New regulations restrict the use of chemicals in areas where vulnerable species live, so well-boats are now being used for this purpose, as the chemicals can be transported away (Svåsand et al., 2017). In addition, chemicals are present due to the machinery, vessels and other equipment, and any spill from these may have adverse effects.

Introgression of genes

Escapes of farmed salmon may have severe negative genetic consequences for the wild stock of salmon in Norway. The wild salmons fitness to survive is compromised by the introgression of genes from farmed salmon, and long term consequences are changes in life-history traits, reduced population productivity and decreased resilience to future changes (Glover et al., 2017). Main causes for escape events are related to structural failures including net tearing which happen during operations and from abrasion from related components (Jensen, Dempster et al. 2010). The sinker tube chain is the most common cause of net tearing, while handling of net weights, including the sinker tube, is the second largest cause (Føre and Thorvaldsen, 2017). Organisational factors that influence escapes have been found to be related to factors such as inadequate training, high work pressure and insufficient risk assessments (Thorvaldsen et al., 2015).

Pathogens, parasites and other

The risk of pathogens being transferred to wild salmon is assessed as low (Grefsrud et al., 2018). The uncertainty of the assessment is however moderate to high because of lack of data or gaps in knowledge. The salmon louse is one of the biggest threats to wild salmon as a result of fish farming, and mortality due to lice infestations is higher among wild salmon than farmed salmon in some areas of Norway. Well vessels, escaped salmon and sea currents may spread both diseases and salmon lice (Brun and Lillehaug, 2010; Hjeltnes et al., 2018).

3.4 Financial losses

The assets exposed to material damage in the fish farming industry include the net cages, their moorings, the feed barge and the service and work vessels. Escaped fish are direct losses for the fish farming companies, and in addition escaped fish must be recaptured, which involves hiring personnel, vessels, equipment etc. Salmon lice challenges are the second highest cost for the industry after feeding costs, and in 2016 delousing treatment costed almost 1.4 billion NOK (Iversen et al., 2017). These costs are the sum of treatment chemicals, operations costs, lost production value due to starvation of the fish prior to operation and mortality of fish due to the delousing process (Iversen et al., 2017).

The fish farming industry is also suffering from loss of reputation. As in other industries major accidents may have direct economic consequences and should be regarded as a priority for industry (Kyaw and Paltrinieri, 2015). In particular, the negative environmental impact of fish farming is not well regarded by the general public (Olsen and Osmundsen, 2017; Osmundsen and Olsen, 2017; Thorvaldsen et al., 2015). Fish welfare is another topic that is increasingly focused on by the public (Röcklinsberg, 2014), and with the 53 million fish (13.2 % of total production) that died during production in 2017 (Hjeltnes et al., 2018) fish welfare has also become a major reputational concern for the industry.

3.5 Food Safety – human consumption

Chemicals

Sources of risks related to food safety in fish farming caused by operations include chemical products and biological pathogens (Arthur et al., 2009). Residues of chemicals used for salmon lice treatments and other veterinary drugs may present a hazard for salmon meat consumers. The Norwegian Food Safety Authority follows the development of the consumption of medicines, and has seen no indication that these have any effect on food safety as of yet (Norwegian Food Safety Authority, 2017).

Biological hazards

Potentially hazardous biological agents for consumers include salmonella in the feed for farmed fish. However, due to low concentrations and fasting before slaughter, it is very unlikely that this bacteria would be found in fresh salmon flesh (Lunestad et al., 2007).

4 Characteristics of major accidents

This section lists characteristics of major accidents, based on definitions of such events. These characteristics are discussed in the light of the risks present in Norwegian fish farming with the aim of finding which characteristics are relevant to a definition of a major accident.

4. 1 Definitions of major accidents

The definitions presented here are those that already exist in regulations or are used by regulatory agencies for the offshore petroleum industries, in Norway and the UK (PSA, 2013; HSE 2015c). In addition, only the definition of major accident related to chemical hazards in the UK is listed (HSE 2015a), because of similarities to the Norwegian equivalent definition. The aim is to find a definition of major accidents in fish farming that may be used as a common ground for the authorities and the industry.

The regulations focus on the type of accidents that take place in the offshore petroleum and process industries, mainly those involving hazardous substances. As mentioned above, this is an inherent difference from the fish farming industry as hazardous substances are neither the product of the industry nor are used in similar quantities. However, we focus on the characteristics of the definitions, not only the "anatomy" of the specific types of accident in the different industries.

The definitions of major accidents in European process industries are largely based on the Seveso III Directive, regulating major chemical accidents. The Norwegian and UK offshore oil and gas sectors regulations have been developed following specific major accidents, and took shape in accordance with the performance-based co-regulation principle (Baram and Lindøe, 2013; Pitblado, 2011). In the performance-based regulation, the level of ambition is set out in the regulations and it is up to the industry itself to comply, often through following industry-accepted standards of best performance practices.

Other industries, such as the maritime, railway and aircraft industries, also experience major accidents, though no clear definition of major accidents are in widespread use in regulating these industries, although terms such as "ship accidents", "railway accidents" and "aircraft accidents" are used in regulations. The Norwegian Maritime Authority, for example, registers all accidents as either a ship accident or a person injury, and a ship accident may include one or more person injuries.

In the literature, the term major accident is not widely debated. In most cases a definition is presented, often based on regulatory definitions, and then used as a basis when presenting major accident theories, causes and prevention methods. However, Okoh and Haugen (2013) discuss aspects included in some major accident definitions, summed up as five key elements; (i) mode or magnitude, (ii) event type, (iii) impact, (iv) timing of impact and (v) impact location (Okoh and Haugen, 2013). These are used as a starting point for identifying some characteristics of major accidents, based on how they are defined in regulations; see Table 2, and discussion in Section 4.2.

Table 2 Major accident characteristics, descriptions and references.

No.	Characteristic	Description	Reference
1	Mode	Acute	(PSA, 2013)
		Uncontrolled developments, loss of control	(HSE UK, 2015a; PSA, 2013)
2	Accident type	Explosion/Fire	(HSE UK, 2015a, c; PSA, 2013)
		Emission/Release of dangerous substance	(HSE UK, 2015a, c; PSA, 2013)
		Damage to structure	(HSE UK, 2015c)
		Failure of diving life-support system	(HSE UK, 2015c)
		Loss of well control	(HSE UK, 2015c)
3.1	Potential consequence	With a significant potential	(HSE UK, 2015c)
		Leading to serious danger	(HSE UK, 2015a)
3.2	Actual consequence	Death	(HSE UK, 2015c; PSA, 2013)
		Serious personal injury	(HSE UK, 2015c)
		Environmental incident/harm to the environment	(HSE UK, 2015c; PSA, 2013)
		Damage to structure	(HSE UK, 2015c)
4	Timing of impact	Immediate or delayed	(HSE UK, 2015a; PSA, 2013)

5	Impact location	Inside or outside the establishment/off-site consequences	(HSE UK, 2015a)
6	Quantification	Several serious injuries	(PSA, 2013)
		Five or more fatalities	(HSE UK, 2015c)

4.2 Major accident characteristics

(1) Mode

Major accidents are described in terms of being acute and uncontrolled in the definition by the Norwegian Petroleum Safety Authority (PSA) (PSA, 2013). The type of accidents that cause major consequences in the offshore petroleum industry, such as major emissions, fires or explosions which in most cases are intrinsically acute. In the UK Control of Major Accident Regulation (COMAH) (based on the Seveso III Regulation), the focus is on the uncontrolled development of the event (HSE UK, 2015a). Uncontrolled developments are included in the guidance for the COMAH regulation referred to, as internal or external events that the operator is unable to control, such as weather conditions, or on/site events that have escalated to a state outside normal operating conditions.

In our interpretation, the two terms “acute” and “uncontrolled” events are used to differentiate events that are abnormal, or outside legal boundaries, from events that are inherent in operations. Acute releases, for example, contribute to acute pollution that is not legally permitted, while some pollution must be allowed for the installations to be operated (PSA, 2017a). Controlled or deliberate events with severe adverse consequences are either sabotage, illegal or inadequately regulated and must be prevented by means of other or additional measures than uncontrolled events. Controlled releases of some treatment chemicals have been allowed in fish farming, though these are now more limited as a result of new regulations.

Acute and uncontrolled definitions may be useful to distinguish major accidents from “normal” events in the aquaculture industry; e.g., mass mortality of fish in operations, injuries and fatalities of operators, loss of vessels, escape events and possibly also infections of pathogens. However, it is worth noticing that for some of the risk dimensions in fish farming, the cumulative effects of minor events may add up to have very serious consequences. For example, contamination due to salmon louse infection and pathogens is gradual, first within the net cage, then to other net cages on the same farm, to farms in the same fjord and to wild fish. In the case of salmon louse infestation the fish should be deloused at a given level of infection. Depending on the pathogen, the fish in whole net cages or even farms may need to be slaughtered. The environmental impact of fish farming can also be cumulative, but they often also disperse in the course of time. In such cases, even though the long-term consequences of exposure may be serious, they can hardly be characterized as acute.

Fish welfare issues may in cases be described as acute, while in other cases the nature of events is more ambiguous. Noble et al. (2018) provide an example of a scenario in which the cause of increased mortality of fish newly released into the net cage is not clearly identified, and the increased mortality is accepted in the anticipation that fish health will eventually stabilise. By the end of production, the initial and additional infections had led to a cumulative mortality of 40% during production. In this situation, it is not evident whether an infection should be regarded as a major accident or not, at least not according to the major accident characteristics, as the infection may be acute, but the overall consequences are not evident until the end of the production cycle. In this case, the fish farmer also had a certain degree of control over the situation and could have slaughtered the fish earlier to prevent unnecessary suffering, so the event may not be seen as «uncontrolled».

(2) Accident type

The definitions identify typical major accident types such as explosion, fires, emissions/release, damage to structure, failure of life support and loss of well control. These types of accidents are of course relevant as major accidents due the inherent properties of the type of production in the process and offshore petroleum industries. Such accidents are not common in Norwegian fish farming. However, there is a potential for fires to break out on feeding barges or living quarters. Recently, an escape event was also caused by fire on the net cage (kyst.no, 2018). With the prospect of larger and more exposed production platforms in the future, fires or explosions might become more relevant aspects, due for example to on-site storage of chemicals. Currently, in fish farming the most notable types of accident are related to personnel injuries and fatalities, vessels capsizing, fish escapes and sudden fish mortality (Holen et al., 2018a, 2018b).

(3) Consequences

(3.1) Potential consequences

The accident types referred to are emissions, fires or explosions with major losses, but such events may also happen without major actual losses. According to the definitions, these events will still be counted as major accidents. The potential of the accident is thus important. This is also emphasized by using terms such as “with a significant potential” and “leading to serious danger”, which imply that no actual damage needs to have occurred for the accident to be counted as major. The potential of the accidents is related to aspects such as the hazards present in combination with the system’s design and accident anatomy (Rasmussen, 1997). It is important to include potential major accidents, as there is a significant potential for learning and future prevention of such events (Hale, 2002).

(3.2) Actual consequences

The consequence categories of the definitions are related to the consequences to people, environment, and material. The actual resulting consequences to people in the definitions are death and serious personal injuries. In the definition from the UK Safety Case regulation (HSE UK, 2015c) the environmental aspect is dependent on there also being consequences for personnel or material. Also damage to physical assets is set as an actual consequence of major accidents. The consequences mentioned in the definitions are all relevant to accidents in fish farming. In addition, consequences for the farmed fish themselves should be added.

(4) Timing of impact

The timing of the impact may be immediate, delayed or both. The COMAH regulation guidance (HSE UK, 2015b) clarifies that the delayed effects should be possible to link to a single acute exposure, release or event. This may be relevant in relation to consequences to human health, however, the environmental effects related to e.g. introgression of genes are not usually possible to link to single escape events. In some events related to infection of pathogens it may be difficult to assess the source of contamination. Often pathogens have been present for a long time in the fish before a diagnosis is made, and in some cases a diagnosis cannot be determined.

Escape events have immediate consequence of loss for the company besides the delayed effect of introgression of farmed fish genes into wild salmon. Fish welfare accidents related to delousing operations have been found to cause acute injury to the fish during the operation, resulting in higher mortality rates after the operation. Table 3 lists some short- and long-term consequences for fish farming, and shows that both time-scales are relevant in fish farm-related major accidents.

Table 3 Some short term and long-term consequences.

Risk dimension	Short-term consequences	Long-term consequences

Fish welfare	Economic loss, mass mortality, ethical consequences/ loss of reputation	Increased mortality, regulatory restrictions, regulatory restrictions in reduced possibility of producing in an area, loss of reputation
Personnel safety	Fatality, serious injuries, loss of work time	Impaired life quality and disabilities, fatalities, loss of reputation
Environment	Economic loss, loss of production, ethical consequences/loss of reputation, mortality of species in surroundings affected by chemicals	Genetic interference with wild salmon, loss of species in the near environment, loss of reputation
Economic loss	Lost assets, lost revenues, loss of marked value	Lost production possibility, loss of reputation
Food safety	Acute diseases Loss of reputation	Death, impaired life quality, loss of trust in governmental control system, loss of reputation

(5) Impact location

Consequences of major accidents are located both inside and outside the facility where an accident happens. Even though the definition from PSA does not explicitly include off-site consequences, they are not excluded.

Off-site consequences are especially relevant for the environmental consequences of fish farming which will naturally have consequences which go beyond the limits for the fish farm. For example, the introgression of genes from escaped salmon to wild salmon, the spreading of pathogens and effects of release of chemicals on wildlife around the fish farm have off-site effects. Food-safety is another inherently off-site risk that spread from the fish farm to society. With regards to fish welfare, the consequences are restricted to local effects, though the pathogens and salmon lice that can infect both farmed and wild salmon may also have environmental consequences. Accidents that have consequences for human health are mainly local, and the widespread consequences in major chemical accident industries are not relevant to fish farming. However, personnel engaged in an activity on or in connection with the installation may be harmed in a major accident, as included in the UK Safety Case regulations definition (HSE UK, 2015c). The fish farming industry is increasingly using subcontractors, and any accident with major consequence potential for subcontractor's personnel should be included as a fish farming major accident.

(6) Quantification

The definition of a major accident from the HSE Safety Case regulation is based on five or more fatalities (HSE UK, 2015c). However, this only applies in relation to work processes, and not in relation to other hazard sources such as explosions and fire. The PSA definition (PSA, 2013) states that a major accident cause several serious injuries and does not number fatalities.

The quantification of losses may be used to distinguish which accidents should be considered in assessments (HSE UK, 2015c) or be investigated. However, the quantification of loss in major accidents may be controversial, both with regards to the possibility of not putting sufficient effort into learning from incidents that have an unrealized major accident potential, as they are not categorized as major accidents (Saleh et al., 2010), and because such limits are always debatable. An ethical question also arises from quantifying the number of lives affected by an accident and the value of a life: is the value of one life impaired or lost in an "occupational" accident less important to prevent, than the material damage in an explosion?

Based on the above characteristics, the following is proposed as definition of major accidents in fish farming:

- An acute event occurring on a fish farm, in the course of its associated activities, or as a result of external impact. The event causes or has the potential to cause, immediately or after a delay, serious injury or fatalities to persons, major damage to the farm or associated vessels, substantially reduced welfare or mortality for a large number of fish, serious environmental harm and/or health problems for consumers of farmed fish.

5 Discussion of the major accident definition for Norwegian fish farming and possible implications.

This section discusses the major accident definition with regards to accidents that have occurred in the aquaculture industry, seeking to explore accidents that fit the definition and some of the causal factors of these accidents. Major risk regulation is important for the prevention of major accidents, and some differences between the offshore and aquaculture sector regulations are pointed out. One of the core strategies in the offshore regulation aimed at preventing major accidents is to identify and maintain barriers, and we discuss this strategy for its potential application in the aquaculture industry.

5.1. Discussion of the major accident definition and accidents in fish farming

The personnel injuries and fatalities are not quantified or defined in plural. A quantification might be relevant for the process and oil and gas industries, from which the definitions are derived, to distinguish the type of accidents that arise from hazards related to chemical process activities from directly work task-related injuries (fall, cuts, entanglement, etc.). In the fish farming industry, the most serious personnel hazards are related to work activities such as operations involving vessels and cranes (Holen et al., 2017a, b), whose consequences usually affect one or two operators. Accidents like these are often regarded as occupational accidents or "simple accidents", and are believed to have causal factors that were under the control of the victim (Jørgensen, 2016). However, unlike major accidents such events are seldom analysed for root causes and possible preventive measures are therefore neither identified nor usually conveyed to operators (Jørgensen, 2016).

Some studies suggest that distinguishing between major and occupational accidents should be replaced by a focus on the hazards that led to the accidents (Bellamy, 2015; Leclercq et al., 2018). A focus on the underlying hazards might provide more opportunity for learning and identifying relevant safety barriers, as incidents may be precursors to major accidents within the same hazard category (Bellamy, 2015). The most important factor is that all safety challenges should be dealt with via systematic efforts according to severity. In 2013, an accident that resulted in one fatality and one serious injury occurred during a maintenance operation on a fish farm. The accident was investigated and the official report (AIBN, 2015) mentioned causes such as inadequate work procedures and risk assessments, and pointed out that a more thorough analysis might have revealed the need for other preventive measures or safety barriers. Training, and the company's knowledge of the competence of its own workers, were also inadequate. This investigation shows that accidents with few victims also have causes beyond the immediate causal factors, and that a systemic approach towards preventing accidents in fish farming is necessary.

It is not easy to single out major accidents related to salmon welfare, though as the core part of production it should be included in a definition of major accidents in fish farming. The welfare of the fish is constantly challenged through external factors, and several choices are made during production that may either improve or impair fish welfare. Some hazards are constantly present, and some are acute and often present in fish-handling operations, and these are included in the major accident definition. This complicates the inclusion of pathogens and salmon louse as causes of major accidents, as already mentioned in Section 4.2. Even though these are seen as some of the most serious threats to fish welfare they tend to be cumulative rather than acute, and opportunities for controlling the development of infestation are much greater than for more acute accidents. However, delousing operations following salmon louse infestations are acute serious threats to the welfare of salmon.

The Norwegian Food Safety Authority received almost 400 notifications about occurrences of poor fish welfare, injuries and fish deaths after delousing operations in 2016, while in 2017 this number was 625 (Hjeltnes et al., 2018; Norwegian Food Safety Authority, 2017). There are no official reports about such events, so their causes are not easily identified. However, the media reported on some events, such as when almost 130,000 fish died during delousing with hydrogen peroxide (NTB, 2016b). New methods, such as thermal and mechanical delousing, are coming into wider use, as resistance in the salmon louse to chemical treatments is increasing. These methods have also led to high fish mortality, such as a case of thermal delousing in which almost 95,000 fish died (NTB, 2016a). The methods that are used to replace the chemical de-lousing have been developed rapidly, and fish farm vets are worried about our limited knowledge of the hazards associated with them (Poppe et al., 2018).

The effects of some environmental impacts of fish farming can be rather subtle and cumulative (GESAMP, 2008). Such impacts should be regulated with a view to their long-term effects. One example of environmental impacts is the release of delousing chemicals, which has long been permitted. However, due to mortality of species living in the vicinity of fish farms, regulatory restrictions of use have been made (Ministry of Trade, Industry and Fisheries, 2008). Where major accidents are concerned, the environmental consequences, as is the case with personnel injuries and fish welfare, are limited to acute and uncontrolled releases of fish or chemicals.

Escapes have serious consequences and are one of the most serious environmental effects of fish farming (Svåsand et al., 2017). One of the largest escape events in Norway occurred in relation to a delousing operation, and almost 175,000 fish escaped. The operation had been ongoing almost continuously for three days, with very little time for the operators to rest. Contributing factors to the accident were stress, long working hours without rest, harsh weather conditions and inadequate inspection following the operation (Norwegian Directorate of Fisheries, 2011).

There are no known cases of major accidents affecting food safety in Norway. Most food safety issues are related to accumulation of chemical toxins that salmon have consumed in their feed or through the environment, and these are not to be considered as major accidents according to the definition.

This discussion makes it fairly obvious that preventing major accidents will not be sufficient to eliminate all hazards for people, fish and the environment. However, nor is this the case in the other industries from which the definitions have been gathered. Prevention of major accidents is only part of a risk management regime. In the process and offshore sectors, it is important to include major accidents as a concept because often safety has originally been associated with managing occupational safety mainly. In the aquaculture industry, too, greater focus on major accidents emphasises that a holistic approach should be implemented. Inadequate risk and safety management in fish farming has frequently been pointed out as contributing to fatalities and escapes (AIBN, 2014, 2015; Thorvaldsen et al., 2015). Investigations into fish welfare accidents are not publicly available, although some contributing causes may be attributed to the fast development of new technologies and methods that have not been sufficiently evaluated for hazards and risks (Poppe et al., 2018). Risk assessments in fish farming today is often focused on specific equipment, without the operational context being taken sufficiently into account, and lacking the systemic aspects such as adequate planning and competence to perform risk assessments (Holmen et al., 2018). A more systemic approach where risk and safety assessments are included in all life-cycle phases such as planning, construction and the operational phase should be developed to prevent accidents in this industry. Moreover, safety and risk management require a holistic approach in that various safety objectives must be evaluated in connection with each operation. In delousing operations, for example, fish welfare, personnel safety and environmental concerns are all central considerations, which sometimes may also conflict.

5.2 Major accident risk regulation approaches in the Norwegian offshore oil and gas and aquaculture industries

The Norwegian offshore oil and gas industry has a well-defined understanding of major accidents, which provides a foundation for different authorities such as the environmental and petroleum safety authorities to cooperate in reaching the common goal of having no accidents. The PSA requires a holistic risk management, where both the design and operation of installations must be considered, in addition to the various potential consequences of accidents (PSA, 2017a). A similar holistic perspective of risk and regulation in fish farming has been highlighted as important by several instances (Osmundsen et al., 2017; Robertsen et al., 2016; Safetec Nordic AS, 2017; Utne et al., 2017).

The regulatory framework in the sea-based fish farming industry is built on the same performance-based principles as in the offshore industry. However, contrary to the offshore regulations, in fish farming regulations there are few direct requirements regarding risk analysis (see Section 2.2), and the only acknowledged standard is NS9415 (2009), which includes requirements to perform analyses in the planning and construction phase aimed at preventing escapes, however with limited reference to risk assessments. In the Norwegian offshore regulations, in addition to direct risk requirements, references to recommended standards and best practice documents are given in the guidelines. The Risk and emergency preparedness assessment-standard (NORSOK Z-013), for example, describes general requirements to risk assessment, and requirements for Quantitative Risk Analysis (QRA) in the concept selection phase, concept definition phase, detailed engineering phase, and the operational phase. Also other standards are developed to guide safety related decisions (Johansen and Rausand, 2015). There are thus several sources for guidance to risk analysis in the offshore petroleum industry. The lack of guidance and requirements regarding how risk assessments should be carried out in relation to fish farm design and operation may lead to insufficient focus and quality of the assessments that are made. If performance-based regulations are not complemented by standards and other guidance, the regulation in itself will be no more than an empty shell (Lindøe, 2007).

In view of the serious hazards and major accident potential in the fish farming industry today and in the future, further developments of requirements to risk assessments addressing major accident prevention in regulations and standards should be evaluated by the authorities and other central actors in the industry. The previous discussion in this paper points to underlying causes to major accidents which require a holistic approach for prevention. Throughout the lifecycle of the fish farm accident preventions strategies should be found by inclusion of organizational, human and technical factors. By focusing on a holistic accident definition, the different relevant authorities also have the opportunity to cooperate on establishing common strategies for prevention of accidents in the fish farming industry, which covers the different risk dimensions. The offshore industry safety regulations may be used as reference, as requirements in regulations have been developed based on a systemic approach, and also in this industry several authorities have to cooperate to achieve a holistic safety regulation structure. The specific industry characteristics must of course be adjusted and adapted as the hazards and accident severity potential in the two industries differ substantially.

5.3 Barrier management

Different risk management strategies to prevent major accidents are implemented in the offshore regulations. One of these is the use of barrier systems and barrier management, which the Directorate of Fisheries is increasingly interested in for adapting to a regulatory strategy against escape events (Norwegian Ministry of Trade Industry and Fisheries, 2017). The identification and management of barriers in the fish farming industry could be useful as a component of a systems based risk management strategy for dealing with other major accident events also beyond escapes.

A good understanding of the major accidents scenarios is essential to the design and establishment of effective barrier systems in the fish farming industry. Our proposed definition of major accidents can contribute to generating the accident scenarios that should be considered. Systematic hazard identification and past experience may be used to identify relevant hazards and threats, triggers and hazardous events that can be systematically collected. There is a potential to set up physical and technical barriers to prevent major accident scenarios from occurring in the fish farming industry, but again, the scenarios should be clearly defined and the effectiveness of the barrier systems should be evaluated. For each hazardous event (e.g., structural failure while workers are working on the floater), the possible proactive and reactive barrier systems can be identified as in place or missing. Barrier failures are also used as indicators of weaknesses in the defense against failure (PSA, 2017a). In the fish farming industry, the main measure of safety is the LTI rate, which alone is a poor indicator of major accidents. Safety indicators related to barrier failures may be more suitable as indicators of changes in safety levels, even before accidents occur.

In today's situation, safe operations in fish farming are heavily dependent on operators' skills and experience (e.g., supervision), which can be termed as a human/operational barrier system according to Sklet, (2006). The case study by Yang et al. (2018) shows that few physical and technical barriers are in place today to prevent and mitigate the consequence of hazardous events such as service vessels colliding with the farm installations or fish escapes. With adjustment and customization, the barrier management framework of the offshore petroleum industry offers a good reference system for the fish farming industry, especially as new-generation offshore fish farms come into operation. Offshore fish farms are already in production and more are expected soon (Norwegian Directory of Fisheries, 2018). The holistic approach of barrier management may be beneficial to the fish farming industry where oversight into the complexity of production hazards is needed. The different risk dimensions relevant to major accidents should also be assessed in relation to each other, and a barrier perspective will make it possible to incorporate better human/operational accident prevention with a holistic consideration of the different hazards.

5.4 Increased focus on major accidents in safety management.

One reason for the need for an explicit separation between major and minor accidents is that occupational safety has been used as a proxy for measuring other types of safety. For example, the easily understandable and measurable lost-time injury (LTI) rate has been used to demonstrate a generally safe workplace, as was the case of the Macondo blowout in the Gulf of Mexico in 2010. On the day of the blow out, a delegation of company VIPs were discussing the outstanding performance of the rig from a standpoint of safety and drilling performance, as no LTIs had been registered for the previous seven years (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). The catastrophic consequences of the blowout show that even though occupational accidents are controlled, which is what is mainly registered on the basis of LTIs, a major accident may well occur.

Major accidents are rare events. In addition, the combination of events leading up to the major accidents is often complex and difficult to foresee. This makes it easier to focus risk management on the events that are easier to understand, and perhaps also easier to prevent, such as occupational accidents. As LTI is the main safety indicator currently in fish farming, occupational safety is also the primary focus. The use of safety indicators is based on the idea that major accidents are preceded by early warnings. A definition of major accidents would increase the focus on such accidents, and act as a reminder that these should be included in risk assessments and management.

In addition to learning from less serious accidents and including factors derived from those used in safety indicator programmes, it is important to anticipate also new and emergent risks. One example is the sudden occurrence of algae along the coast, which may lead to large fish mortality, but is not systematically monitored in Norway (Winther, 2018). There may also be other emergent risks that are not easily anticipated. Catastrophic events that occur as a result of unforeseen circumstances are known as "black swans", because they were never even imagined. This concept may be useful as a reminder that also events that are related to great uncertainty must be taken seriously in risk management (Haugen and Vinnem, 2015).

5.5 Some ethical considerations of major accidents in fish farming

One of the main drivers behind the strategic decisions made in the fish farming industry is to maintain a good reputation and to avoid negative publicity (Vormedal, 2017). As major accidents do not contribute to these goals, but rather the opposite, it is important for fish farming companies to avoid such accidents. While avoiding major accidents is a strategic cost-related decision, it is also an important ethical decision.

In this paper, we argue that there are examples of major accidents in the fish farming industry that may not only entail major hazards to people or the environment, but also to the fish itself. There are significant consequences both in terms of ethics and with regard to costs when major accidents occur. Though until recently it has not been clear to which degree fish can feel pain, it is now well established that fish are sentient beings with complex cognitive abilities (Brown, 2015). Given that very large numbers of fish are held in net cages along the coast of Norway, the number of suffering individuals is potentially very great and efforts must be made to reduce the risk of inflicting pain (Vonne et al., 2007). An issue increasingly in focus within the ethical challenges of fish farming is the use of cleaner fish which is used as a more environmental friendly alternative to chemical delousing (Poppe, 2017; Gonzalez and de Boer, 2017). There are several welfare issues related to the use of cleaner fish, including cases of high mortality, and these are insufficiently investigated (Grefsrud et al., 2018). Besides the day-to-day welfare, a focus on the possible major accidents that may happen to fish is an important part of caring for all animals that are kept for human consumption.

The issue of weighing human safety against fish welfare is another important topic with no easy solution (Röcklinsberg, 2014). Identifying and describing conflicting safety objectives should be an integrated part of a holistic risk management practice (Holen, 2018; Utne et al., 2017). Our major accident definition which includes consequences relevant to aquaculture should help us to affirming the values that need to be protected. In operations there should be clear guidelines for fish farm managers and their operatives to provide support for decision-making.

6 Conclusions

This paper is intended to contribute to a better understanding of *major accidents* in Norwegian fish farming. It is not easy to provide a clear cut understanding of the term in relation to fish farm accidents, but we propose a definition based on the five main risk dimensions in this industry and major accident regulations in other industries. We discuss the definition in relation to hazards and accidents that have occurred in fish farming, and discuss hazards that can be categorized within a major accident definition. Risk management in fish farming must include major accident prevention strategies in addition to the management of long-term risk and sustainability during fish production. Some of the discussed accidents in this article show that there are systemic causal factors contributing to loss. Both regulators and industry are already looking to the offshore petroleum industry to transfer knowledge of technology and management. Barrier management is among the holistic major risk management methods that is seen as a potential way forward for aquaculture, and we reflect on how best to adopt this method to fish farming.

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