



UIT

THE ARCTIC  
UNIVERSITY  
OF NORWAY

Faculty of Science and Technology  
Department of Engineering and Safety

# Assessing the Risk of Escape from Marine Fish Farms

*Improving Data Collection Strategies and Development of Risk Indicators*

—  
**Randulf Høyli**

*TEK-3901 Master's thesis in Technology and Safety in the High North – May 2016*





## Abstract

Marine fish farming is one of Norway's largest industries and exports. The industry is in rapid development and secures employment for several thousand people, all along the Norwegian coastline. Fish farming is regarded as a relative sustainable method for food production. However, the industry is still prone to certain challenges and problems. Escape of fish, for instance, is one of the industry's main challenges and also the emphasis of this thesis. Interactions between escapees and wild populations are unwanted because of potential for interbreeding, competition for food and transfer of disease and pathogens. Financial penalties and damaged reputations are additional downsides related to the escape of fish.

This thesis investigates the risk of fish escape from marine fish farms. The Directorate of Fisheries' database on previous escapes is reviewed and literature studies are performed to reveal particular causes and factors associated with the escape of fish. Furthermore, the concept of risk indicators is utilized in order to provide a means for monitoring the risk of escape. The underlying principle is that by measuring the state of risk-influencing factors (RIFs), it is possible to monitor how the relative risk level develops. However, RIFs are not necessarily directly measurable, thus indicators are developed as tools for measuring the state of RIFs. Consequently, risk-mitigating measures can be implemented at the correct time and the correct place in order to prevent or reduce the probability of escapes.

It is believed that the database on previous escapes may be utilized to a greater extent in preventing future escapes. This may be achieved by, for instance, making the database available to the public and by considering the possibility of including underlying and organizational aspects with potential influence on escapes. However, through assessment of the current method for data collection on fish escapes, it is revealed that the database is prone to certain limitations and challenges. To cope with these challenges, the thesis suggests potential measures in order to improve the validity and general usefulness of the database.

To the author's best knowledge, no previous work exists on the use of risk indicators within marine fish farming. Thus, this thesis relies upon similar works within oil and gas (O&G) to assess the problem. The O&G industry utilizes technical safety barriers to prevent major accidents, e.g. hydrocarbon leaks. These barriers are then candidates for indicator development. However, the only evident technical safety barriers to prevent escapes are the main components of the fish farm itself. This creates a challenge in identifying suitable technical risk indicators. However, organizational and human aspects are more comparable between the industries. In this regard, this thesis proposes a set of indicators and RIFs to monitor the risk of escape from marine fish farms. They are, however, presented without any form of testing, and would benefit from further assessment using field data and expert judgments.



# Preface and acknowledgments

This thesis is the culmination of the two year master program in Technology and Safety in the High North, at UiT - the Arctic University of Norway. It is the final part of the requirements for the degree of Master of Science in engineering.

The thesis builds upon a preliminary project conducted in the autumn of 2015. Both projects are written in cooperation with Safetec Nordic AS in Tromsø, and the topic came during a meeting in October 2015. The author had little previous knowledge within the field of study, but quickly realized that escape of fish from marine fish farms was a serious threat and in need of mitigation. Hence, the topic presented itself as both interesting and challenging, and was carried on onto the master thesis.

During the course of this thesis and preliminary work some people have made significant contributions, and thus some acknowledgments are in order. First of all, my sincere gratitude goes to my supervisor, Masoud Naseri, for his useful comments, remarks and valuable guidance when writing this thesis. Thanks also to Professor Javad Barabady for his valuable advice and contribution in this process. Furthermore, I would like to express my gratitude to the Directorate of Fisheries for granting me access to their database on previous escapes. A big thanks also to Safetec Nordic AS for giving me the possibility to write this thesis with their guidance, and for providing me with relevant material and help in defining the thesis. Others who should be mentioned are external contacts during the preliminary project, for taking their time and providing valuable discussions and relevant material.

Additional thanks goes to my friends and fellow students, for all the good experiences, friendships and inspiring conversations throughout the bachelor- and master studies.

Tromsø, May 2016

Randulf Høyli



# Contents

<b>Abstract</b>	<b>i</b>
<b>Preface and acknowledgments</b>	<b>iii</b>
<b>List of figures</b>	<b>vii</b>
<b>List of tables</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.2 Statement of relevance . . . . .	2
1.2.1 Why the escape of fish is of concern . . . . .	2
1.2.2 Problem statement . . . . .	4
1.3 Aim and objectives . . . . .	4
1.4 Research questions . . . . .	4
1.5 Limitations . . . . .	5
1.6 Organization of thesis . . . . .	5
<b>2 Review of relevant literature</b>	<b>7</b>
2.1 Marine fish farming . . . . .	7
2.1.1 Basic structure of fish farms . . . . .	7
2.1.2 Salmon life cycle . . . . .	8
2.1.3 Some governmental regulations . . . . .	9
2.1.4 Characteristics of appropriate farming locations . . . . .	10
2.1.5 Fish farming operations . . . . .	10
2.1.6 Organizational and human aspects . . . . .	14
2.2 Theoretical framework . . . . .	18
2.2.1 Risk analysis theory . . . . .	18
2.2.2 Concept of risk indicators . . . . .	18
<b>3 Research approach and data collection</b>	<b>27</b>
3.1 Research methodology . . . . .	27
3.2 Data collection . . . . .	28
3.2.1 Historical fish escape data . . . . .	28
3.2.2 Relevant literature . . . . .	28
3.3 Research approach . . . . .	29
3.3.1 Approach for assessing historical fish escape data . . . . .	29
3.3.2 Strategy for development of risk indicators . . . . .	29

---

<b>4</b>	<b>Results and discussion</b>	<b>31</b>
4.1	Method for data collection on fish escapes . . . . .	31
4.1.1	Reporting of events . . . . .	31
4.1.2	Processing of reported escapes . . . . .	32
4.1.3	Structure of the database . . . . .	32
4.1.4	Limitations and potential improvements . . . . .	34
4.2	Investigation of causes for fish escape . . . . .	36
4.2.1	Scope of assessment . . . . .	36
4.2.2	Parameter assessment . . . . .	37
4.2.3	Assessment of causes for previous escapes . . . . .	41
4.2.4	Some final remarks . . . . .	46
4.3	Development of risk indicators . . . . .	46
4.3.1	Identification of risk-influencing factors . . . . .	47
4.3.2	Selection of risk-influencing factors . . . . .	55
4.3.3	Identification of indicators . . . . .	55
4.3.4	Model with RIFs and indicators . . . . .	61
<b>5</b>	<b>Conclusion and recommendations for future work</b>	<b>63</b>
5.1	Conclusion . . . . .	63
5.2	Future work . . . . .	64
	<b>Bibliography</b>	<b>70</b>



# List of Figures

- 1.1 Approved locations for sea-based aquaculture in Norway . . . . . 1
- 2.1 Illustration of a typical fish farm . . . . . 8
- 2.2 Illustration of the different stages in farm salmon life cycle . . . . . 9
- 2.3 Illustration of delousing of fish with tarpaulin and workboats . . . . . 11
- 2.4 Illustration of net cleaning with high-pressure washer . . . . . 13
- 2.5 Strong winds and heavy sea pose a challenging environment for operators  
on marine fish farms . . . . . 15
- 2.6 Illustration of how fish safety may come at the expense of personnel safety. 17
- 2.7 Main steps of the risk analysis process . . . . . 18
- 2.8 Relationship between RIFs and indicators . . . . . 19
- 2.9 Illustration of an indicator that only partly measures the factor. . . . . 20
- 2.10 Illustration of a RIF being measured by a set of indicators . . . . . 21
- 2.11 Methodology for the establishment of technical risk indicators . . . . . 22
- 2.12 A qualitative model as a step in the establishment of organizational risk  
indicators . . . . . 23
- 2.13 The Factor model . . . . . 25
- 3.1 General research methodology for conducting the thesis. . . . . 27
- 3.2 Research approach for developing indicators to monitor the risk of escape. 30
- 4.1 Number of events and escapees in the period 2006-2015 . . . . . 36
- 4.2 Reported escapes sorted by location. . . . . 39
- 4.3 Relative frequency of escape. . . . . 40
- 4.4 The most frequent causes for escape of salmon and trout. . . . . 43
- 4.5 The most frequent causes for escape of cod . . . . . 45
- 4.6 Frequency scoring categories . . . . . 48
- 4.7 Illustration of potential change in indicator value and effect on RIF. . . . . 58
- 4.8 Illustration of potential change in RIF and effect on risk. . . . . 59
- 4.9 Extremes for the indicator ‘lag on follow-up of reported deviations’ . . . . . 60
- 4.10 Model with RIFs and indicators for the hazard ‘net tearing due to interac-  
tions between net and sinker tube’. . . . . 62



# List of Tables

- 4.1 Classification intervals for parameters (a) number of escapees, (b) size of fish farm and (c) depth of net. . . . . 32
- 4.2 Data basis divided by (a) species and (b) size of escape. . . . . 37
- 4.3 The 356 events sorted by month . . . . . 38
- 4.4 Distribution of Norwegian fish farms by location. . . . . 39
- 4.5 Escapes sorted by farm type. . . . . 40
- 4.6 Escapes sorted by farm size. . . . . 41
- 4.7 Escapes sorted by net depth. . . . . 41
- 4.8 Distribution of events by area . . . . . 42
- 4.9 Distribution of events by category . . . . . 42
- 4.10 Top five causes for salmon and trout escapes with respect to (a) the number of events and (b) the average number of escapees . . . . . 43
- 4.11 Distribution of events by component . . . . . 44
- 4.12 Complete overview of the reported cod escapes . . . . . 45
- 4.13 Consequence scoring categories. . . . . 47
- 4.14 Preliminary risk analysis . . . . . 53
- 4.15 Risk-influencing factors. . . . . 55
- 4.16 Proposed set of indicators to monitor the risk of escape. . . . . 56
- 4.17 Hypothetical reporting of non-compliance reports during a one-year period. 60



# Chapter 1

## Introduction

### 1.1 Background

Norway has a long coastal line with good fish farming conditions and is the world's largest producer of farm Atlantic salmon (Marine Harvest, 2015). Aquaculture is also one of Norway's greatest industries and exports, and accounts for more than 9600 work-years (Andreassen and Robertsen, 2014). The industry provides employment to several remote locations and fish farmers are located all along the Norwegian coastline, as illustrated in Figure 1.1. The annual production exceeds 1.3 billion tons of cultured fish, to a value of approximately 44.3 billion NOK (SSB, 2015). Of this annual production, farm salmon is by far the most dominant contributor and accounts for more than 94 % of the total revenue.



Figure 1.1: Approved locations for sea-based aquaculture in Norway (Directorate of Fisheries, nd).

Fish farms may be equipped with complex systems for operations or be dependent on more manual and conservative methods. Some fish farmers prefer hand feeding and close supervision, while others, likely larger companies, rely upon automated systems and tech-

nology. What is certain is that the industry has experienced tremendous growth in the last decade. The number of fish farm locations may have decreased, but the annual production has nearly tripled since the start of the 2000s (Andreassen and Robertsen, 2014; SSB, 2015). The increased demand and modern technology has turned small-scale fish farming, often run as family businesses, into great enterprises with significant revenues and reputation. However, with development comes additional challenges in terms of both operations and safety.

## 1.2 Statement of relevance

### 1.2.1 Why the escape of fish is of concern

Escape of fish is associated with a series of negative consequences and the Ministry of Fisheries and Coastal Affairs (2009) regards it as one of the main hazards within Norwegian aquaculture. The industry has several opposing actors, and political acceptance is key in securing further growth and development. The concerns of fish escapes are mainly with respect to interactions with wild populations, but companies may experience financial and societal consequences as well. Put in perspective, the number of farm salmon in Norwegian sea-based aquaculture exceeds 363 million (Directorate of Fisheries, 2016a), while the number of wild salmon that spawn in Norwegian rivers restricts to about 500000 to 1 million (Jensen et al., 2010). Furthermore, the world's stock of wild Atlantic salmon has been reduced by 80 % during the last 30 years, and has disappeared from approximately 45 Norwegian rivers (Økokrim, 2008). However, while the aquaculture industry does present a very real threat towards wild populations, it may not be justified to blame this unfortunate development solely on them, as several other factors may have been contributing. Additionally, because approximately one-third of the world's wild salmon population have their spawning grounds in Norwegian rivers, Norway has committed to take special managerial responsibility for the wild Atlantic salmon (Ministry of Fisheries and Coastal Affairs, 2009).

To emphasize the importance of preventing fish escapes, the below sections provide a more detailed description of specific threats. With respect to environmental consequences, Jensen et al. (2010) emphasizes on three main areas of concern:

- Interbreeding
- Competition for food
- Transfer of disease and pathogens

In addition, fish farmers may suffer economic losses and damaged reputation due to escapes of fish.

#### **Interbreeding and genetic interaction**

The Norwegian fish farming industry started in the 1970s and consisted of 40 different stocks of wild salmon (Naylor et al., 2005; Rambøll, 2010) to provide genetic variability. Seventy percent of eggs used in Atlantic salmon farming in Norway today derives from derivatives of the original stocks (Naylor et al., 2005). Consequently, farm salmon has

become less equal the wild salmon, which now has a greater genetic diversity. Interbreeding between the species affects the genetic properties of wild populations (Jensen et al., 2010) and may reduce the survivability of wild salmon (Ministry of Fisheries and Coastal Affairs, 2009). However, crossbreeding is not always successful and depends upon the farm salmon's ability to ascend rivers, access spawning-grounds and spawn successfully (Jensen et al., 2010).

Fleming et al. (2000) did a large-scale experiment, releasing sexually mature farm and wild salmon into the river Imsa in southwestern Norway. With no salmon present in the area prior to the experiment, results indicate that invasion of farm salmon has the potential for reducing the genetic diversity of wild salmon, as well as influencing the population productivity. Through modelling based on the results from these experiments, Hindar et al. (2006) states that even after decades without further intrusion, wild populations may not recover from previous interactions with escaped salmon; wild stocks may eventually become mixtures of hybrids and farm descendants.

### **Competition with wild fish**

Despite having a significantly inferior ability to reproduce than wild fish (Fleming et al., 2000), escapees pose a threat to native populations through competition for the same resources. With similar diets, both wild, farm and hybrid fish compete for the same food (Fleming et al., 2000). In addition, farm salmon compete for the same spawning areas as wild fish (Rambøll, 2010) and may prevent the native salmon from reproducing. Despite suffering high mortality, the escaped salmon's offspring outgrow their native counterparts (Hindar et al., 2006) and thus may have a competitive edge over the wild juveniles. Furthermore, farm juveniles have shown greater aggression and risk-taking, causing increased stress on, and leading to displacement of, the native fish (Naylor et al., 2005).

### **Transfer of disease and pathogens**

Sea lice exists naturally in marine waters and are a threat to both farm- and wild salmon (NEA, nd). Fish farms present an ideal environment for the formation and transmission of sea lice (Torrissen et al., 2013) and the probability of infection is likely greater in large densities of fish. Transmission of disease and parasites to wild populations may occur through escapees or through wild fish migrating close to fish farms (Naylor et al., 2005). The spread is unwanted as sea lice can disrupt the fish's salt balance and give reduced growth, reproduction capacity, swimming ability and weakened immune system (Anon., 2012). When contained in fish cages, the parasites are treatable, but infection of wild populations are harder to constrain and the lice can spread over large distances through ocean currents.

### **Economic and social consequences**

Escape of fish is an unwanted and criminalized event with potential economic and criminal consequences for both companies and employees (Thorvaldsen et al., 2013). According to the Norwegian aquaculture operation regulation (Akvakulturdriftsforakriften, 2011), fish farmers are obligated to report any suspicion of escape to the Directorate of Fisheries. Failing to report, or tampering with numbers, are criminal offenses and punishable by Norwegian law (Ministry of Trade, Industry and Fisheries, 2013). In addition to financial

penalties, large resources may be required to recover the escaped fish and damage to farming equipment can be costly. Loss of reputation is an additional consequence that may affect both companies and the industry as a whole. Failing to prevent major accidents produces bad press and makes it harder to gain political acceptance.

### 1.2.2 Problem statement

With a constantly increasing world population, the need to acquire sustainable food sources is of crucial importance. Fish farming has emerged as a relatively sustainable method for food production. However, as argued in the above sections, fish escapes pose a challenge for the industry's continued growth. Hence, it is requisite to prevent fish escapes in order to preserve wild populations and ensure political acceptance for further growth. Thus, further research on preventing escapes is necessary to secure a sustainable and environmentally friendly development. In this regard, evaluating the risk of escape may play a key role in establishing rules and regulations to prevent escapes.

## 1.3 Aim and objectives

This thesis aims to investigate measures to reduce the probability of fish escapes from marine fish farms. Historical data on fish escapes are analyzed and the thesis highlights important causes for the escape of fish. In particular, the thesis looks at the concept of risk indicators and how it may be applied to monitor changes in risk level with respect to the escape of fish.

More specifically, the objectives of the thesis consist of:

- Reviewing and discussing the current approach for data collection on fish escapes, and further proposing some recommendations aiming at data collection improvement for mitigating the risk of escape.
- Assessing the causes for fish escape from marine fish farms.
- Applying the concept of risk indicators to develop a means for monitoring the risk of escape from marine fish farms.

## 1.4 Research questions

Based on the stated aim and objectives of this thesis, the following research questions are identified:

1. How can data collection on fish escapes be improved to be utilized in mitigating the risk of escape?
2. What are the main factors contributing to the escape of fish?
3. How can the concept of risk indicators be utilized in order to reduce the probability of escape from marine fish farms?



## 1.5 Limitations

Escape of fish may occur in all stages of production, but the thesis only considers escapes occurring during rearing in marine fish farms. Escapes from land based facilities and onshore lake farms are outside the scope of this thesis. Furthermore, fish farms with open, net-based solutions where water flows freely in and out of the cage are the only type considered in this thesis.

The thesis discusses potential consequences of fish escapes, but does not emphasize on measures to reduce these consequences. Instead, the focus is on preventing escapes by reducing the probability of occurrence.

The database on previous escapes has its own limitations, which are described and discussed separately in Section 4.1.

The indicators are developed with the purpose of providing a means for monitoring the risk of escape. They provide no means for monitoring the risk towards human safety. Additional indicators must be developed specifically for this purpose, or other safety measures may be applied.

## 1.6 Organization of thesis

In addition to the introduction given in chapter one, the thesis consists of the following chapters:

Chapter 2 is a review of relevant literature. The reader is introduced to marine fish farming, basic risk analysis theory and the concept of risk indicators.

Chapter 3 presents the research methodology and data collection for this thesis.

Chapter 4 presents the results of this thesis where the three main objectives are discussed.

Chapter 5 is the conclusive part of the thesis with recommendations for future work.



# Chapter 2

## Review of relevant literature

The first section of this chapter gives an introduction to the concept of marine fish farming. The reader is introduced to the basic structure of fish farms, the salmon life cycle and common operations within fish farming. Furthermore, governmental requirements and regulations are discussed, the characteristics of suitable farming locations are mentioned and some organizational and human aspects are pointed out.

The second section presents the theoretical framework with some basic risk analysis theory and an introduction to the concept of risk indicators. However, to the author's best knowledge, no previous attempts exist on implementing the concept of risk indicators within the fish farming industry. Consequently, this thesis relies upon relevant research from other industries.

### 2.1 Marine fish farming

#### 2.1.1 Basic structure of fish farms

This thesis considers marine fish farms with open solutions where water flows freely in and out of the cage. The farms are either square steel-constructions or circular plastic-constructions. Plastic cages are mentioned to have advantages in terms of behavior in waves and are often preferred when farms exceed 160 m in perimeter (Aarhus et al., 2011). Furthermore, certification according to Norwegian Standard (2009) is more extensive and expensive for steel plants. Consequently, plastic cages are becoming increasingly prevalent in Norwegian aquaculture.

Fish farms may consist of a number of parts, but NYTEK (2012) defines the major components of marine fish farms as:

- Floating collar
- Fleet/barge
- Net/cage
- Moorings

Figure 2.1 illustrates a typical fish farm with weights to suspend the net. Fish farms may also have sinker tubes instead of weights, and are commonly situated alongside each other with combined mooring systems. Furthermore, there are systems for fish feeding

and mort collection with different degree of automation. Additionally, some farms have cone shaped bottoms, while other are more flat bottomed, as in Figure 2.1. The floating collar (No. 2, Figure 2.1) has its function to support loads from the net, and serves as the most rigid part of the construction. The net/cage (1) contains the fish, while weights (4) or a sinker tube provides suspension and volume. A railing net (3) prevents fish from jumping out of the cage, and farms are often equipped with additional protection nets for predators.

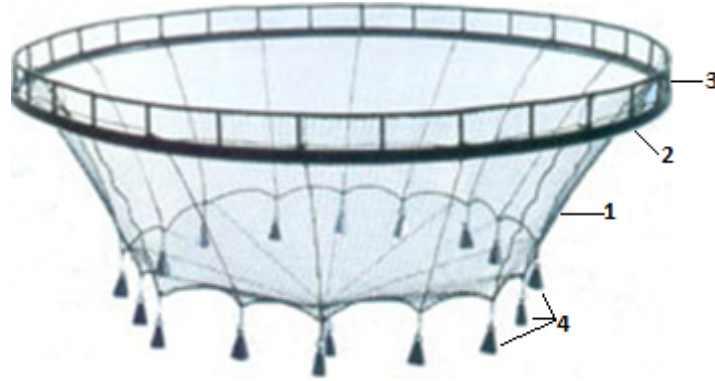


Figure 2.1: Illustration of a typical fish farm. Photo adapted from DELWP (n d).

Fish farms have become increasingly automated following the technological development in recent years. Modern farms are now more reliant upon complex systems for operations, and may have feed barges with control rooms, living quarters and integrated systems for fish feeding (Akvagroup, 2015a). The modern facilities can provide convenient working conditions for operators, but there are still companies that utilize traditional and manual methods for fish farming.

### 2.1.2 Salmon life cycle

Farm salmon goes through several stages before it is grown and ready for processing. This usually takes between 27 and 42 months (Laksefakta, 2015) and may involve several companies, specializing at different stages of production.

Fish eggs are fertilized in small freshwater tubs in onshore hatcheries. When the fish hatches, it lives off a yolk sac for about four to six weeks before it starts accepting external feeding. At this stage of production, the fish is moved to larger tanks and referred to as fry. After having grown to about 60 to 100 grams and being habituated to seawater, the fish is ready for rearing in marine fish farms and is called smolt. The next 14 to 22 months is spent in floating sea farms where the salmon grows to about 4 to 6 kilos before it is slaughtered and further processed (Laksefakta, 2015).

An illustration of the farm salmon's life cycle is shown in Figure 2.2. Here it goes from freshwater hatcheries (roe, fry and smolt production) to sea-based growth and finally to slaughter, processing and export.

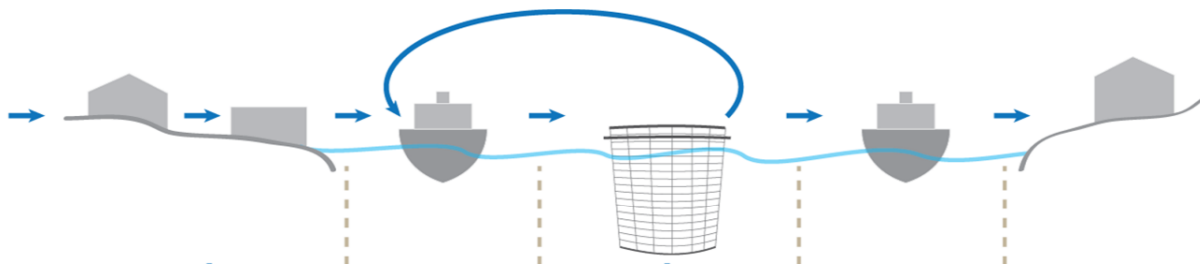


Figure 2.2: Illustration of the different stages in farm salmon life cycle. Adapted from Bjelland et al. (2012).

The life cycle from land-based growth to rearing in the sea and final processing in onshore plants are indicated by the arrows in Figure 2.2. The different stages may be divided as:

- Roe delivery and hatching in onshore hatcheries
- Onshore fry/smolt production in larger tanks
- Transport to marine fish farms
- Sorting/splitting into farms with appropriate mesh sizes during growth
- Transport to harvesting plants for slaughter and processing

### 2.1.3 Some governmental regulations

The NYTEK-regulation (2012) is a national regulation for certification and inspection of fish farm systems. It sets technical requirements for fish farming installations and shall prevent the escape of fish. The Ministry of Fisheries and Coastal Affairs<sup>1</sup> issued the regulation, but the Directorate of Fisheries is responsible for enforcing it. The regulation entered into force 1st of January 2004 and was later updated and republished in 2011<sup>2</sup>.

NYTEK refers to Norwegian Standard (2009), i.e. NS 9415, for requirements on site survey, risk analyses, design, dimensioning, production, installation and operation of floating fish farming installations. The standard states that sites are categorized based on significant wave height, peak wave period and current velocity. It further requires location-specific measurements with respect to current velocity and direction, wave parameters, wind velocity and direction, tidal forces, and water depth and topography. The standard also sets requirements for main components and day-to-day operations.

Furthermore, there are regulations for internal control (IK-Akvakultur, 2005), which requires companies to document their planning, organizing and implementation of measures to fulfill the Aquaculture Act. Holmen and Thorvaldsen (2015) argues that the regulation involves the most important formal requirements related to the prevention of fish escapes.

<sup>1</sup>The Ministry of Fisheries and Coastal Affairs was closed down and superseded by the Ministry of Trade, Industry and Fisheries 1st of January 2014 (SNL, 2014)

<sup>2</sup>The updated regulation came into force 1st of January 2012 (NYTEK, 2012)

### 2.1.4 Characteristics of appropriate farming locations

Both environmental and societal interests should be taken into consideration when new locations for fish farming are awarded. These locations must be approved by the Norwegian Government, and fish farmers are required to obtain licenses for the given areas, according to Laksetildelingsforskriften (2005). Bjerkestrand et al. (2013) discuss different aspects of importance when selecting locations for fish farming. Some of these are:

- Fish welfare
- Environmental impact
- Impact on the local community
- Area utilization
- Working conditions for operators

Most fish farms in Norway are located in coastal areas sheltered from harsh weather and sea. However, with new technology and research, the industry is looking to move farther offshore to strengthen the biological conditions and reducing the environmental consequences of fish farming. This generates a need for new and stronger structures able to withstand greater winds, currents and waves. Furthermore, the operational conditions are more extreme and may set new safety regulations and requirements for procedures and fish handling. However, it also creates a unique opportunity for further growth and development within sea-based aquaculture.

### 2.1.5 Fish farming operations

Fish farming is a complex process and involves a number of operations and different types of equipment. The physical environment may be challenging and operators are expected to handle both fish, machinery, equipment and chemicals in a satisfactory manner. Certain activities are associated with particular risk and may require extra planning and coordination. These critical operations must be performed with care and are often subjected to strict procedures where safety job analyses (SJA) are required. In addition, net controls are mandatory after activities with particular risk of net damage.

#### Sorting, splitting and counting

Counting of fish happens in all stages of its life cycle; during egg-fertilization, in hatcheries, during growth at sea and before slaughter. It is often performed as a part of other operations like sorting, splitting or delousing of fish (Bjelland et al., 2012). Wellboats may be used in cases of sorting and splitting, and as the smolt grows, it should be transferred to larger farms. However, it is important that new cages have appropriate mesh sizes in order to avoid escapes.

#### Towing operation

Towing operations may be used when transporting grown fish to the harvesting plant. However, it is described as a risky operation and should only be performed when absolutely necessary (Høiseth et al., 2009). If the fish first must be transferred to a towing-cage, it is done by sewing two cages together and creating a ‘tunnel’ for the fish to swim through (Directorate of Fisheries, 2015d). By using a special net, which is dragged across the

cage by two workboats, the fish is forced over to the new cage. When all the fish are moved to the towing-cage, the tunnel is removed and the net reattached. The towing may now begin, but before starting the operation it is important to raise both weights and mort collector to avoid contact with the seafloor (Directorate of Fisheries, 2015e). It is essential to map the seabed topography and to be aware of own draft before the towing starts (Høiseth et al., 2009). The Directorate of Fisheries (2015e) generally recommend constant supervision over fish, cage and net, as well as additional personnel and assistant-boats to avoid accidents during towing of fish cages.

### Delousing processes

Formation of sea lice is a significant threat for the fish farming industry. The lice can damage the fish and are responsible for enormous economic losses to the aquaculture industry (Skiftesvik et al., 2013). In severe cases, formation of sea lice may result in mass deaths and can spread to wild populations or between fish cages in near proximity of each other. Mitigation is performed through delousing processes at irregular intervals, depending on the amount of lice present in the fish cages. The most common approach for estimating the infestation is to inspect a simple random sample of fish (Heuch et al., 2011). The delousing process is often performed with drugs administered through food, or with chemicals baths (Stien et al., 2016) where either wellboats or tarpaulins provide containment. In either case, the fish should be sufficiently starved to keep it calm and reduce its need for oxygen (Luseprosjektet, 2013). However, chemicals are expensive and the lice may develop resistance to such treatment (Stien et al., 2016). An alternative method is by the use of cleaner fish, which has emerged as a robust method for treating salmon lice (Torrisen et al., 2013). An illustration of delousing of fish with tarpaulin is given in Figure 2.3.

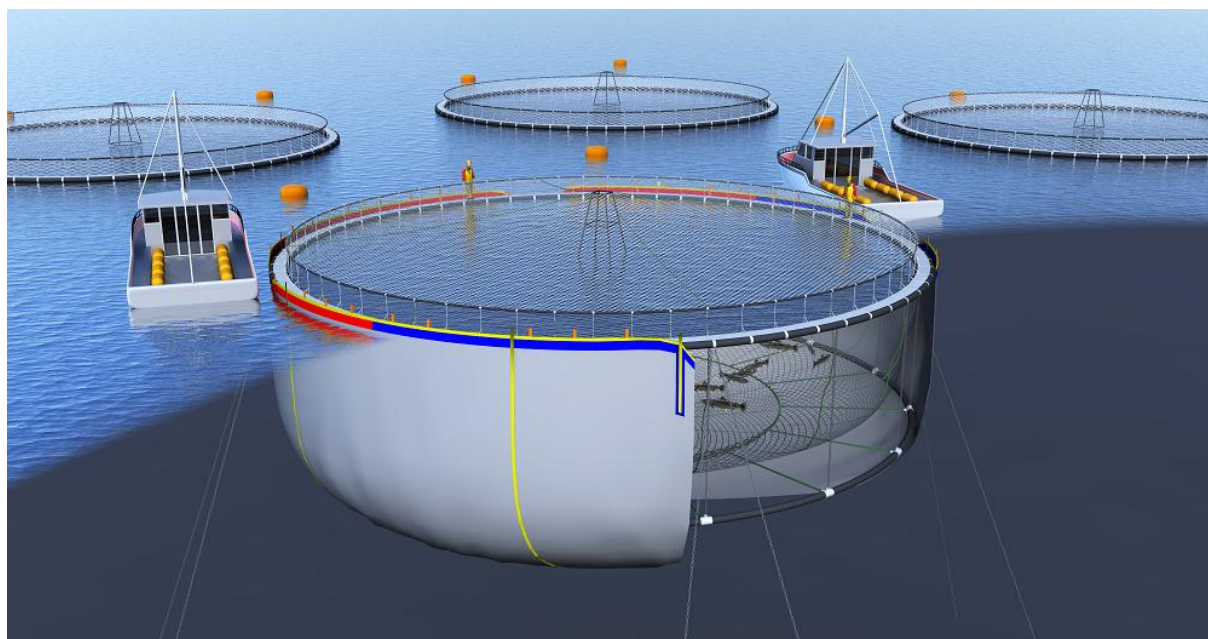


Figure 2.3: Illustration of delousing of fish with tarpaulin and workboats. Photo by Botngaard AS (2013).

#### *Delousing with tarpaulin*

During delousing with tarpaulin, the net is raised and the tarpaulin is dragged under the

net. This ensures containment and chemicals may be pumped into the cage. It is recommended that four boats, where at least two are equipped with cranes, are present during the operation (Luseprosjektet, 2013). Furthermore, the process involves a high number of workers and consists of critical operations related to boat maneuvering and net handling. In addition, the oxygen level must be under constant monitoring to ensure fish welfare (Luseprosjektet, 2013).

### ***Delousing with wellboat***

During delousing with wellboats, the fish is crowded in a restricted area and pumped into a tank (or well) on the boat. When the pumping of fish is complete, delousing chemicals are added and the oxygen level is monitored closely throughout the operation. Lice are counted both as the fish are pumped in and when they are released. This enables the wellboat crew to properly adjust the dosage of chemicals (Luseprosjektet, 2012). Rapid loading is preferred, as confinement puts extra stress on the fish, but the procedure must be performed without hurting the fish. A particular risk associated with wellboat operations are large cranes with considerable strength that may tear nets without operators noticing (Thorvaldsen et al., 2013). Furthermore, the well has several entrances the fish can escape through, and failure of pumping equipment, like hoses, valves or connections, are other potential causes for the escape of fish (Høiseth et al., 2009).

### ***Delousing using cleaner fish***

The use of cleaner fish to maintain low levels of lice has become increasingly prevalent in the recent years (Nilsen et al., 2014). By constantly maintaining low lice-levels, cleaning fishes, such as wrasse or lumpfish, may provide a treatment that are less stressful for the salmon (Deady et al., 1995). In addition, no chemicals are released to the environment and the risk of escape is reduced when complex delousing processes are avoided. Previous research by Skiftesvik et al. (2013) showed that, with a ratio of 5 % wrasse to salmon, the amount of lice was at a very low level. Furthermore, the cleaner fish are bred for a sole purpose of lice treatment, and cultured wrasse have proven to be as efficient as wild wrasse.

## **Mort collection**

There are both automated and manual methods for mort collection. The automated systems can be quite complex and may consist of compressors, hose systems and collector bowls (Akvagroup, 2015b). Manual mort collectors however, may be as simple as a collection-net that is raised with either cranes or winches. The importance of mort collection is related to accumulation of dead fish. The accumulation may induce extra stress on the floating collar and attract predators. Furthermore, it is requisite that the system is properly positioned to avoid damaging the net (Directorate of Fisheries, 2015b).

## **Fish feeding**

Today's systems for fish feeding are highly automated and rely upon sensors to regulate the feeding process (Sunde, 2014). These systems should provide optimal feeding to ensure that the fish receives the correct amount of feed at the correct time in order to avoid both under- and overfeeding. This is essential to preserve the environment, save costs, and ensure proper growth.



### Net change and net cleaning

Fouling may reduce the throughput of water and give insufficient oxygen levels in fish cages. In addition, strong algae growth induces extra loads on the floating collar and may cause a complete breakdown of the cage construction (Akvagroup, 2015c). Furthermore, net fouling, for instance in form of mussels, may weaken the net and increase the risk of net damage with subsequent risk of escape (Bjerkestrand et al., 2013). Consequently, there is a need for periodic net cleanings or changes to ensure fish welfare and cage integrity. The frequency of net cleanings depends upon the environmental conditions at the given location, and may differ from one area to another. Frequent cleaning provides clean nets free of algae, but may also induce wear and reduce the nets' lifespan (Bjerkestrand et al., 2013). Hence, it is important to be aware of the degree of fouling and ensure that worn out nets are either repaired or replaced. An illustration of net cleaning with high-pressure washer is given in Figure 2.4.

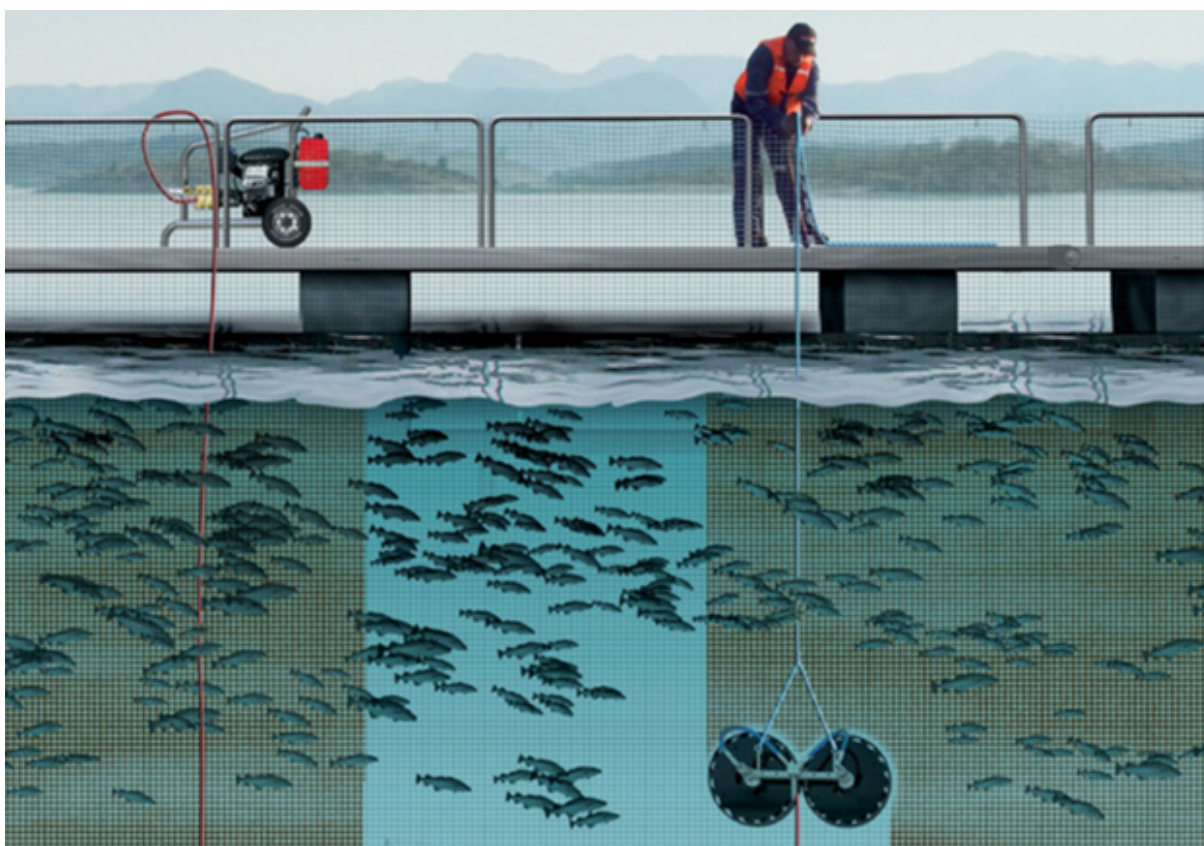


Figure 2.4: Illustration of net cleaning with high-pressure washer. Photo from Akvagroup (2015c).

#### *Net cleaning*

Net cleaning may be performed by a variation of procedures, either at sea or in large washing machines. The latter requires a full detachment of the net, while cleaning at sea may be performed with high pressure washers. The rotating cleaning discs are pushed against the net cage and high-pressured water is forced out through nozzles on the discs (Føre and Lien, 2014). Thorvaldsen et al. (2013) states that cleaning efforts have been reduced after the introduction of new net-cleaning methods. However, new technology may introduce additional hazards and challenges with respect to the escape of fish. For

instance, Føre and Lien (2014) identifies several direct causes for net damage during cleaning in sea. First, they mention that cleaning equipment occasionally get stuck in the net and may lead to tearing of holes; second, that sharp edges in the equipment may cut the net; and last, that pressure and wear from cleaner discs may fray and weaken the net cage.

### *Net change*

Changing of nets may be performed by threading a new net around the old one (Directorate of Fisheries, 2015c). This procedure involves removing weights and releasing the mort collection system to allow the new net to be pulled under the old one. The old net is hooked off and the new one attached to the floating collar on one side of the cage. After dragging the net across, the old net may be completely removed and the new one attached around the cage. As with other operations, potential hazards are related to workboats, cranes and interactions with net. ROVs or divers are used to ensure that weights and mort collection system are properly positioned. In addition, it is important to control for net damage that may have occurred during the operation.

## **2.1.6 Organizational and human aspects**

Fish farmers are subjected to a number of organizational aspects that may set conditions for successful operations and prevention of escapes. However, human beings are also prone to certain influences with potential for increasing the risk of mistakes. It has been argued by Øien et al. (2011) that previous incidents in the O&G industry could have been prevented with proactive thinking and a focus on underlying organizational aspects. Hence, this section aims to highlight factors with influence on human performance and to emphasize the root-cause potential of organizational aspects.

### **Human performance and impact from bad weather**

The human performance is highly influential and potentially affected by factors like harsh weather and external pressure. Wind, low temperatures and societal conflicts are just some of the factors that can influence the human performance. Furthermore, the actual temperature range that humans are ‘designed’ to operate in is very narrow (Markeset, 2013). Consequently, several conditions should be met in order for humans to operate and function at a desired level.

When working on marine fish farms, there are many dangers and potential for accidents. The working environment is tough and may expose operators to strong winds and heavy sea, as illustrated in Figure 2.5. The harsh weather adds additional risk to an already challenging work environment, and special attention is required when posed to these extreme conditions. Plastic fish farms are constructed without outer railings, and gateways may become slippery when exposed to seawater or icing. Furthermore, the workspace is limited and confined to a narrow gateway surrounding the farm. Operations involving cranes and workboats are a particular risk during bad weather, where operators can lose control of the steering and stuck cranes may go unnoticed. Furthermore, the fine motor skills are reduced when personnel are tired, cold or in other ways excessively fatigued. All these aspects accumulate to highlight the importance of the human performance when it comes to staying safe and avoiding mistakes.

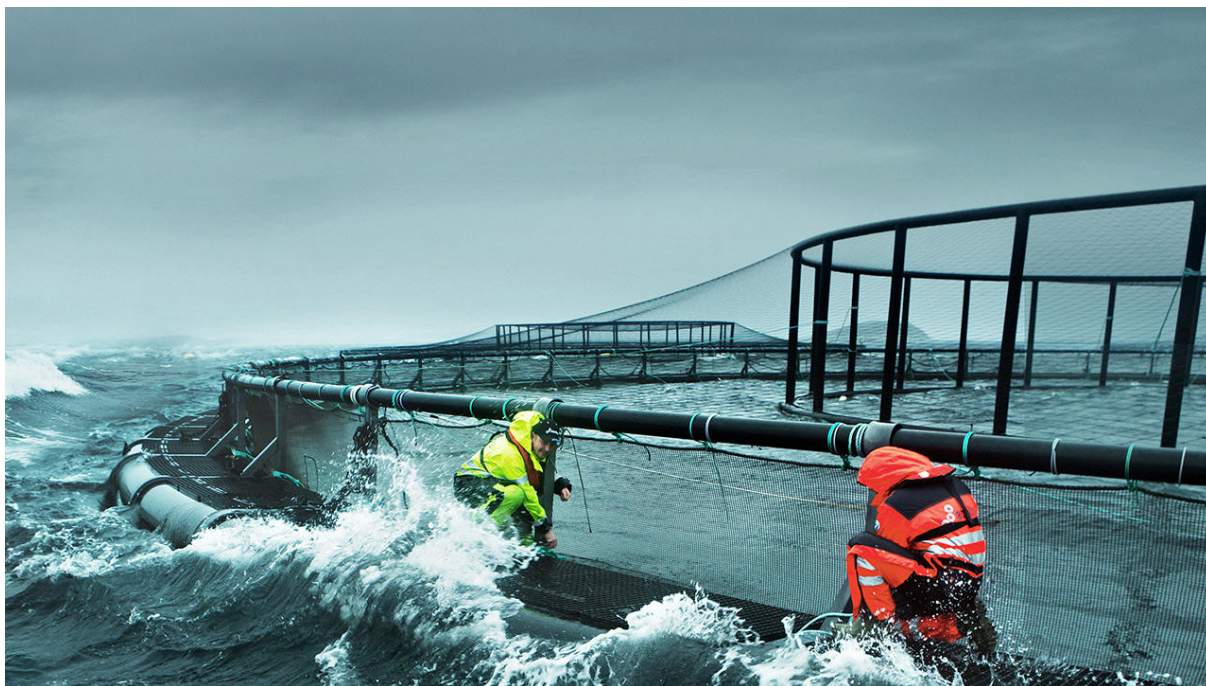


Figure 2.5: Strong winds and heavy sea pose a challenging environment for operators on marine fish farms. Photo from Aqualine (2015).

Fish farmers carry great responsibilities with respect to fish welfare and safety. Thus, it is requisite that personnel are given the required rest and are not overworked to the degree where it apparent puts them at risk. Tired and exhausted personnel are essentially not just a danger to themselves, but also to those around them.

#### *The special case of the Arctic region*

The Arctic region is known for its long winters, cold temperatures and seasonal darkness. Ice, snow and winds are known characteristics that may lead to difficult operating conditions. The Arctic region may be defined by the Arctic Circle (Zolotukhin, 2014), and, by this definition, all areas north of  $66^{\circ}\text{N}$  are located in the Arctic. Norway's geographical area ranges from  $57^{\circ}\text{N}$  to  $71^{\circ}\text{N}$  (SNL, 2015), and fish farms are located from the very south to the far north of the country, as illustrated in Figure 1.1. As of February 2016, approximately one-fifth of the operating fish farms in Norway are located in the two northernmost counties, Finnmark and Troms (Directorate of Fisheries, 2016b). An additional 630 farms, or 19.4 %, are located in Nordland. With this widespread distribution of fish farms, it is clear that companies may experience large differences in operating conditions, and thus need location-specific procedures and guidelines. Special care is required for fish farmers in the high north, where snow, wind and ice set additional requirements for safe operations. Cold temperatures and strong winds increase the need for heavier clothing and may reduce the mobility of operators. Operations and tasks are made more challenging when motoric skills are reduced, and the risk of mistakes increases. In addition, the cold weather may affect equipment and cause embrittlement of materials (Markeset, 2013). Furthermore, long winters and darkness increase the amount of workhours performed in inadequate working conditions, and reduced vision can be a threat in any operation.

## Organizational aspects

After the introduction of the NYTEK-regulation, escapes related to structural failure have significantly decreased (Aarhus et al., 2011). However, the industry still experiences major accidents, and a subsequent focus on organizational aspects and human factors have emerged. This is emphasized by Thorvaldsen et al. (2015) who focus on how organizational factors may influence the escape of fish. Additionally, Holmen and Thorvaldsen (2015) look at how other industries conduct safety work in order to identify measures to prevent escapes from Norwegian fish farms. A focus on organizational aspects as early warning signs for major accidents is not a new phenomenon. It has been utilized in other industries, which should indicate a need for fish farmers to emphasize the importance of organizational aspects with respect to the prevention of fish escapes.

### *Training and competence of personnel*

The experience of personnel can often be regarded as a measure of their competence. While it may not be accurate in all cases, it is a fair assumption in general. Having experience involves knowing which factors and hazards to be aware of under critical operations. It reduces the risk of accidents and highlights the importance of learning from past mistakes. A potential concern is the industry's development with respect to higher degrees of technology, where experienced fish farmers may become 'inexperienced' when confronted with this new and modern technology. Fenstad et al. (2009) further states that the formal education given to fish farmers provides limited experience in performing practical operations like the use of lifting equipment. Additionally, experienced operators and recruits are often put in pairs during the training phase, but there are no formal arrangements for transfer of experience to new operators; it is rather described as something that '*happens by itself*'.

### *Workhours, time pressure and planning of operations*

Thorvaldsen et al. (2013) describes situations with long workhours and insufficient staffing, often associated with larger operations. These operations are often associated with particular risk of escape and involve many workers and thus require thorough communication, cooperation and planning. Fish farmers are a part of a larger process involving several actors dependent on each other. Consequently, situations may occur where harvesting plants put time pressure on fish farmers to deliver. Everyone works to achieve the same goal, but it is important that the management understands the situation out on the farm and avoids setting unrealistic time frames for operations.

### *Deviations and procedures*

Filing non-compliance reports is essential in terms of learning from past mistakes and improving operational procedures. By documenting what causes accidents and near misses, it is possible to detect trends and prevent future accidents from happening. However, the level of reporting among operators are not consistent; Thorvaldsen et al. (2015) cites a fish farmer saying '*Some reports a knot that has come undone, others do not report unless there is a hole in the net cage*'. This is a major concern and companies should have clear guidelines on what operators should report.

### *Organizational safety culture*

A high focus on preventing escapes should be prevalent throughout the organization, all the way from the 'blunt end' (management) to the 'sharp end' (operators). Everyone must

be provided a clear reason as for why mitigation is important and explained the benefits of reducing fish escapes. In addition, personnel that contributes to an increased safety level should receive positive recognition. Consequently, this may increase the personnel's motivation for emphasizing the importance of risk mitigation, as well as contributing to a 'thinking safety' culture within the organization. The Institute for Work & Health (2011) emphasizes that safety should be considered at least as important as production and quality. In the fish-farming industry, fish safety is closely linked with quality and profit; ideal water conditions and a stress-free environment provides farming conditions where the fish may thrive. In addition, escape of fish has direct impact on production, and consequently, it is in the fish farmer's best interest to focus on fish welfare and the prevention of escapes.

### *Personal safety vs fish safety*

While preventing escapes and ensuring fish safety is of great importance, it should not come at the expense of personal safety. However, research has shown that operators sometimes prioritize fish safety over personal safety because of severe consequences following fish escapes (Thorvaldsen et al., 2015). This is illustrated in Figure 2.6. Such prioritizing may lead to procedures not being followed and increase the risk towards human safety. Furthermore, time pressure is mentioned as a contributing factor and Størkersen (2012) emphasizes that management relies upon fish farmers to make all of the practical safety-decisions in operations.

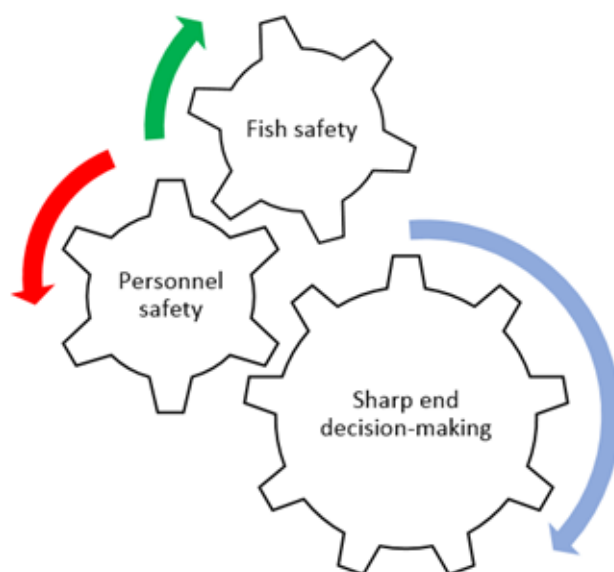


Figure 2.6: Illustration of how fish safety may come at the expense of personnel safety.

An example is made of two fish farmers about to start feeding when they discover a contorted pole on a fish farm. They are left with two choices; ensure personal safety by following procedures, but at the same time prolonging operations and exerting potential harm to the fish; or improvise, ensuring fish safety and avoiding overtime. The latter involves increased personal risk by performing repairs without the necessary safety-equipment and illustrates how fish safety may be prioritized over personal safety. However, there are situations where increased fish safety means less risk for man. Ensuring this relation in all operations would make sharp-end decision-making less critical. In addition, a set of absolute operational decision-parameters may provide a means for increasing the personal safety within Norwegian aquaculture.

## 2.2 Theoretical framework

### 2.2.1 Risk analysis theory

#### Description of risk

Risk may be understood as a measurement of the potential loss occurring due to natural or human activities. It is often described as a combination of the probability of occurrence of harm and the severity of that harm (IEC, 2013). Risk may also be used to express the danger that undesirable events represents to human beings, the environment and economic values (Aven, 1992).

#### Risk analysis

A risk assessment is one of the main steps of the risk analysis process, illustrated in Figure 2.7. The assessment consists of hazard identification, cause- and consequence analysis and finally an illustration of risk, e.g. through a risk picture. Also included in a the process are planning and risk treatment.

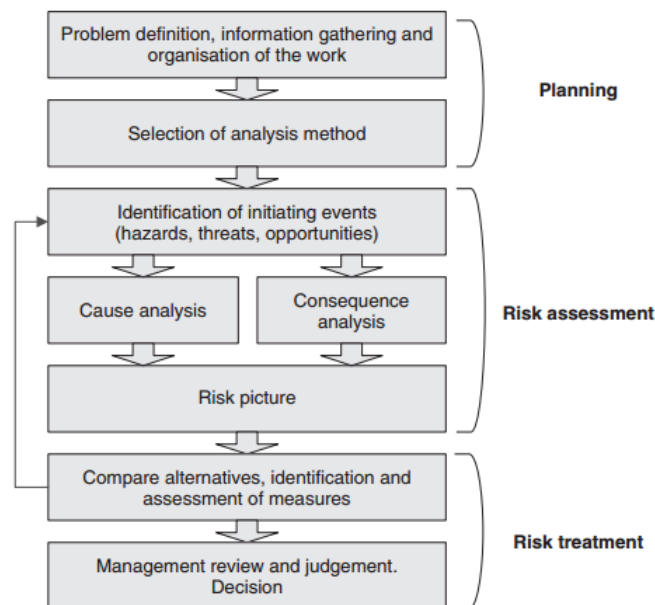


Figure 2.7: Main steps of the risk analysis process as described by Aven (2008).

This thesis investigates the risk of escape from marine fish farms and aims to utilize the concept of risk indicators as a measure for mitigating the risk. Consequently, both planning and a potential risk treatment measure are determined by the aim and scope of the thesis. The risk assessment however, is performed through a preliminary risk analysis (PRA). The specific PRA approach is described in Section 4.3.1.

### 2.2.2 Concept of risk indicators

This section introduces the reader to the concept of risk indicators and presents two strategies on how indicators may be developed to monitor the risk level at a given installation. The concept of risk indicators is prevalent in many of the world's major industries, and this thesis utilizes existing research from the O&G industry to explain the phenomenon.

In fact, the establishment of risk indicators is a mandatory action within the O&G industry, according to regulations set by the Norwegian Petroleum Directorate (Øien and Sklet, 2001b).

### Indicators for major accident risk

Indicators may be defined as ‘measurable or operational variables that can be used to describe the condition of a broader phenomenon or aspect of reality’ (Øien, 2001). They are utilized in order to reduce the risk of major accidents and rely upon recognizing warning signs at an early stage (Øien et al., 2011). Early-warning indicators are often of an organizational nature and rely upon underlying causes with limited direct safety relevance (Øien et al., 2011). Technical indicators however, may be based on an existing quantitative risk assessment (QRA) and are of a more direct nature. Nevertheless, the common objective is to prevent major accidents by measuring changes in risk level (Øien and Sklet, 1999). However, of importance is that indicators do not necessarily give information on all risk aspects in a system; other measures for evaluating risk- and safety levels should be used in combination to ensure safety for both man, environment and assets.

On a general basis, the main purposes for using indicators (Øien et al., 2011) is:

- To monitor the level of safety in a system (e.g. a department, a site, or an industry)
- To decide where and how to take action
- To motivate those in a position to take the necessary action to actually do it

In the way it is applied above, a major accident may be described as an acute and unplanned event with potentially severe consequences for either humans, the environment or economical assets (Haugen et al., 2012). This study recognizes the escape of fish as a major accident and argues that prevention is necessary in order to preserve the environment, save costs, and secure political acceptance.

### *Risk-influencing factor*

A risk influencing factor is defined as ‘an aspect (event/condition) of a system or an activity that affects the risk level of this system or activity’ (Øien, 2001). However, not all RIFs are measurable, thus indicators are utilized to describe the conditions of risk-influencing factors. The relationship between a RIF and an indicator is illustrated in Figure 2.8.

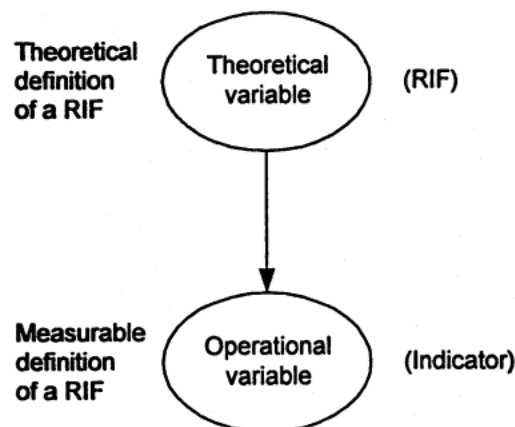


Figure 2.8: Relationship between RIFs and indicators (Øien, 2001).

### ***Safety indicators and risk indicators***

Øien et al. (2011) make a point of distinguishing between safety indicators and risk indicators. They argue that ‘if RIFs are included in a risk model, it is possible to determine the effect on risk (measured by some risk metric) of a change in the indicator value of a given RIF’. In these cases, the indicators are described as risk-based. However, if no risk model is available, the effect on safety must be related to measures other than risk metrics, for instance the number of accidents or pure qualitative measures. These indicators are then denoted safety-indicators and may be selected based on an assumed effect on safety or through correlation. This thesis restricts itself to consistent use of the denotation ‘risk indicator’, but does not emphasize the distinction between the two types.

### ***Leading and lagging indicators***

A lagging indicator may be described as an after-the-event type of indicator, which, for instance, counts the number of accidents or near misses. A leading indicator however, looks further back into the causal chain at underlying causes and attempts to provide feedback before an accident occurs (Øien et al., 2011). This distinction between ‘lead’ and ‘lag’ has been discussed in a number of papers and there are different opinions of the importance of distinction between the two. However, HSE and CIA (2006) emphasizes the importance of utilizing both types and refer to the approach as ‘dual assurance’ (Øien et al., 2011).

### ***Requirements for indicators***

Several researchers have developed sets of criteria for indicators as to secure that they perform their intended function. Based on previous research, Haugen et al. (2012) suggest that indicators should meet the following requirements:

*Validity:* There must be a clear relation between the indicator and the risk-influencing factor it is supposed to measure. The indicator should co-vary with the status of the RIF and must be able to reflect any changes in the risk. However, some indicators may only partly measure the factor, Figure 2.9, and are therefore not regarded as very good indicators.

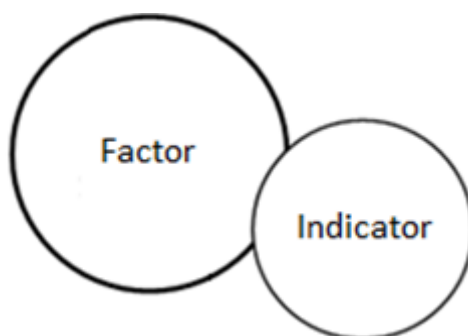


Figure 2.9: Illustration of an indicator that only partly measures the factor.

*Measurability:* An important attribute of an indicator is that it is measurable. It is preferred that changes can be expressed quantitatively, but in the very least, it should be possible to classify the status qualitatively through different degrees of grading.

*Comprehensibility:* An indicator is connected with a risk-influencing factor and the link



between them should be intuitive and easy to understand. It is essential for the personnel in day-to-day operations to understand what the actual meaning of the indicator is and what variables that should be measured.

*Reliability:* An indicator must be reliable in the sense that changes in the status reflects actual changes in the RIF and not changes in the measuring process.

*Additional requirements:* Indicators are used to measure changes in risk, but, at the same time, it must be possible to take action based on these measurements. Hence, an indicator should be useful in a way that it is possible to influence its status. Additionally, there is the question of costs; a good indicator is likely to give certain benefits, but the cost of establishment (research, data collection, etc.) and maintenance (updating, measurements, etc.) must not exceed the benefits.

A factor is not necessarily limited to be measured only by one indicator. It happens that indicators only measure a fraction of the factor and in such cases, a *set of indicators* may be used, Figure 2.10. These sets of indicators have their own requirements and Haugen et al. (2012) lists the following evaluation criteria for a complete set of indicators:

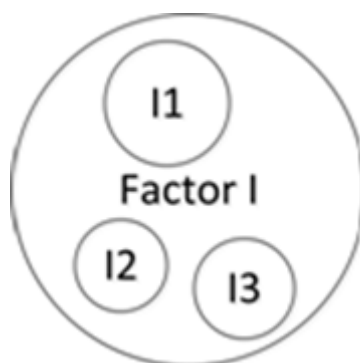


Figure 2.10: Illustration of a RIF being measured by a set of indicators (Haugen et al., 2012).

*Size of indicator sets:* An indicator set must be large enough to measure the RIF in a satisfactory manner, but extensive use of indicators can be both time-consuming and costly - making the whole operation unprofitable.

*Dual assurance:* Dual assurance is an approach that combines the use of leading and lagging indicators where the aim is to measure the present status of a factor and at the same time give early warning signs of potential accidents.

*Alarm and diagnosis:* It is desirable with a combination of alarm- and diagnosis indicators in an indicator set. Alarm indicators state if something is wrong while diagnosis indicators are more specific and give information on what is wrong.

*Frequency of measurements:* The frequency of measurements depends on the nature of the indicator. Some require monthly measurements, while others are more suited for quarterly or even annually measurements. A set may contain indicators of different kinds, but should consider the costs of frequent measurements.

## Strategies for development of risk indicators

This section presents methodologies from two previous projects on how to develop indicators for major accident risk. The methodologies shall provide a theoretical foundation for establishing a set of risk indicators to monitor the risk of escape from marine fish farms. However, neither the Indicator Project (Øien and Sklet, 2001b) nor the Factor Model (Haugen et al., 2012; Nyheim et al., 2012) are targeting the fish farming industry, which may create additional challenges.

### *The indicator project*

SINTEF completed a number of relevant studies in the late 90's, early 00's in a project called 'the Indicator Project'. This project was written on behalf of the Norwegian Petroleum Directorate (NPD) and involved pilot projects on Ekofisk 2/4-T and Statfjord A in 1994 and 1996, respectively (Øien and Sklet, 2001b). The project also included separate reports by Øien and Sklet (1999, 2001a) with procedures for the establishment of technical- and organizational risk indicators, respectively.

The methodology for developing technical risk indicators is divided into eight systematic steps, Figure 2.11. Both the selected accident and the risk-influencing factors are identified based on an existing QRA. However, the indicators are developed to monitor changes in risk, and not the total risk level on the facility (Øien and Sklet, 1999). In other words, they monitor the risk relative to the risk level established in the QRA. Consequently, it is requisite that factors have potential for change, and that a change in a RIF displays a change in the total risk level.

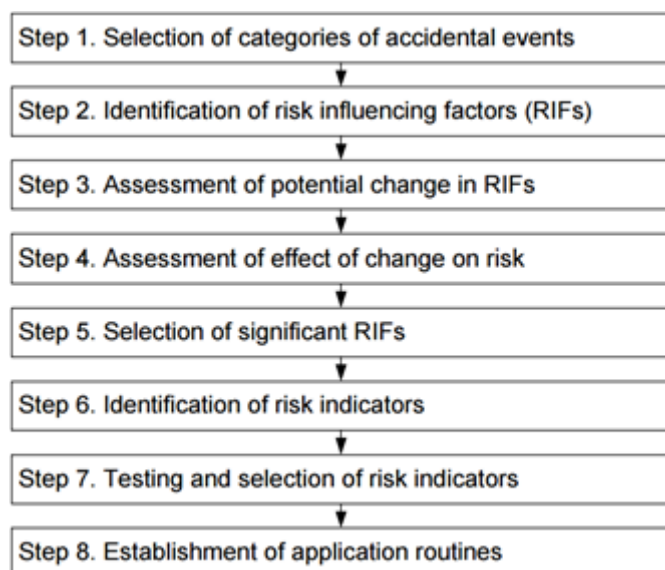


Figure 2.11: Methodology for the establishment of technical risk indicators (Øien and Sklet, 2001b).

The potential effect of change in RIF on risk is assessed through a sensitivity analysis, where the QRA provides a basis. However, both software and manual approaches may be applied (Øien and Sklet, 1999). Indicators are assigned to each of the significant factors and must be a measurable variable with the ability to detect changes in their respective RIFs. It is beneficial to select indicators that can be monitored through existing measurements (Øien and Sklet, 1999). The final step involves establishing routines for

measurement and use of the selected indicators. The point in time at which risk-mitigating measures should be performed are decided, and it is emphasized that indicators do not cover all aspects affecting the total risk (Øien and Sklet, 1999).

By establishing technical risk indicators, Øien and Sklet (1999) show that a change in a RIF often can be controlled directly by parameters in the QRA. However, there are cases where changes in risk level cannot be directly measured by technical risk indicators. In such cases, Øien and Sklet (2001a) suggests assessing the changes in risk by measuring changes in organizational factors. A qualitative model is developed as a step in the establishment of organizational risk indicators for the major accident ‘leak’ on an offshore oil and gas installation, Figure 2.12. Øien and Sklet (2001a) suggests the following factors as a foundation for establishing organizational risk indicators:

- Training/Competence
- Procedures, safety job analysis (SJA), guidelines and instructions
- Planning, coordination, organization and control
- Design
- Preventive maintenance (PM) program/Inspection

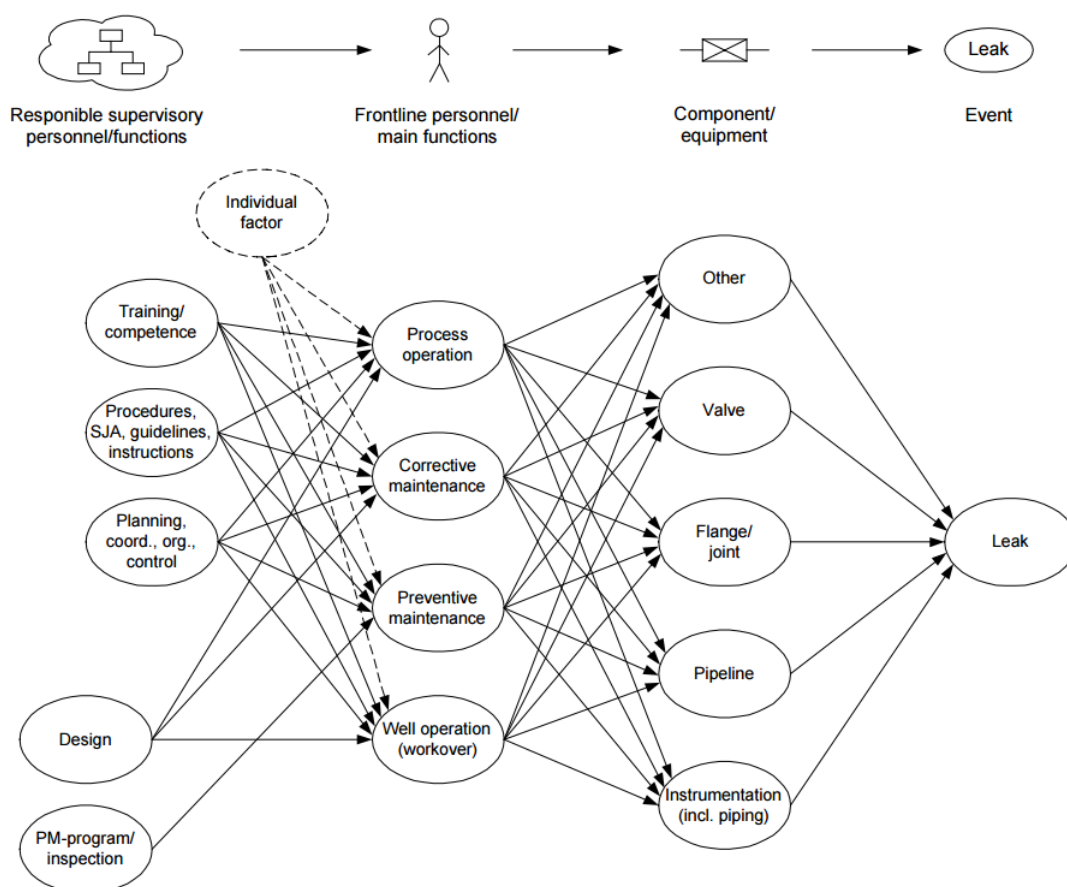


Figure 2.12: A qualitative model as a step in the establishment of organizational risk indicators (Øien and Sklet, 2001b).

As the objective is to assess the change in risk level due to changes in the leak frequency, some sort of quantification is needed. The quantification methodology consists of four steps for estimating the effect on risk due to changes in organizational factors (Øien and Sklet, 2001b):

1. Establishing a quantitative model
2. Assessing the organizational factor states
3. Assessing the impact of the organizational factors
4. Calculating the total effect on the leak frequency

As for the technical risk indicators, the final effect on risk is calculated using sensitivity analyzes based on the QRA (Øien and Sklet, 2001b). It is described as a complex operation, which benefits from the utilization of software.

### *The factor model*

A project on major accident risk indicators was performed in 2012 through a cooperation between the Norwegian University of Science and Technology (NTNU), Safetec Nordic AS and Statoil Norge AS. The basis was obtained from relevant research in former projects, including the Indicator Project, but the project is supplemented with further development. It is divided into two parts:

- Part I: A method for identification of risk indicators (Haugen et al., 2012).
- Part II: Applying this method in a case study on hydrocarbon leaks on a process plant (Nyheim et al., 2012).

The methodology for identification of risk indicators is a systematic approach resulting in a model with both technical and organizational indicators:

1. Identification of major accident
2. Identification of risk influencing factors
3. Linking the RIFs together with arrows showing the influence and the direction of the influence
4. Identification of indicators

Haugen et al. (2012) recommends the use of logical reasoning combined with knowledge of the system to identify risk-influencing factors. They emphasize the use of influence through other factors, e.g. by asking what influences the performance of the navigator instead of looking directly for factors that affect the probability of collision. Furthermore, they suggest utilizing existing risk assessments and data from previous events in the identification process. The results are illustrated in a model with several layers and arrows indicating the direction of influence among factors, Figure 2.13.

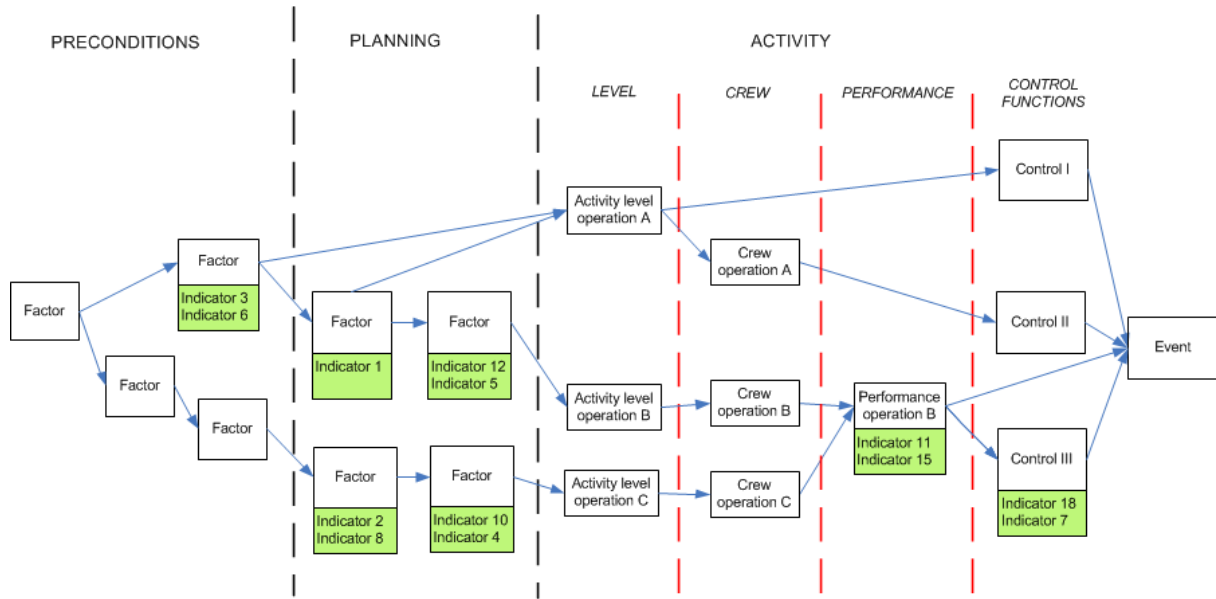


Figure 2.13: The Factor model (Haugen et al., 2012).

Preconditions are factors at a higher level in the company and are either pre-determined or changed infrequently (Nyheim et al., 2012). Planning are activities that sets the conditions for day-to-day operations while the activity layer represents these daily operations (Haugen et al., 2012). Part II is a case study on hydrocarbon leaks where the methodology is applied to identify indicators for a given plant. In the case study, the model is adjusted by dividing the precondition layer into three separate sections fitting to the plant. This suggests that the model is open for manipulation and may be adjusted according to what system is being investigated.



# Chapter 3

## Research approach and data collection

### 3.1 Research methodology

According to Rajasekar et al. (2013) a research methodology is a systematic way to solve a problem. It should illustrate the procedures used for describing and explaining the phenomenon that is being studied. Research methods however, are approaches and tools used to provide specific solutions to the problem. These may include theoretical procedures, experimental studies, statistical approaches, etc. The research methodologies differ from research methods in the way that they are more concerned with the overlying approach or strategy for conducting the research and not focused on specific solutions.

The research methodology for conducting this thesis is illustrated in Figure 3.1. Under each step, case-specific approaches and research tools are utilized in order to satisfy the objectives of each segment.

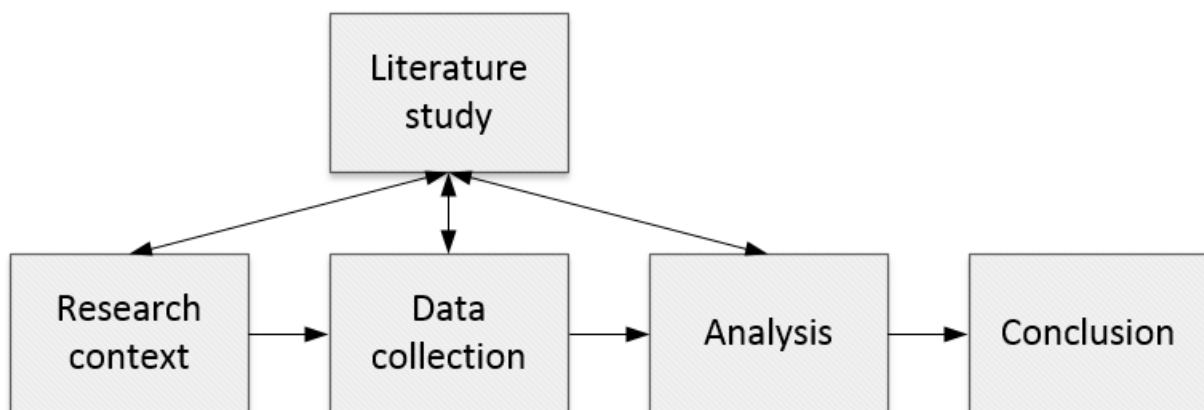


Figure 3.1: General research methodology for conducting the thesis.

*Research context:* Defining the research topic involves determining the area of study, defining aims and objectives and restricting the research in terms of scope and limitations. These aspects are open for changes as the research evolves. That is to say, the field of study should remain the same, but scope and limitations may change depending on how the study develops.

*Data collection:* Data collection is necessary in order to provide background material for the study. For instance, it may be material for literature reviews or statistical data used in data analysis.

*Literature study:* Literature reviews may be performed to find the scientific aspects one wants to investigate further. It may also assist the data collection and provide a theoretical foundation for conducting the analysis. It is essential in any study to acquire knowledge in order to be able to fully understand the phenomenon that is being studied.

*Analysis:* After having obtained the necessary information, the data analysis is conducted. The aim of the analysis can be to verify or test important facts, to find solutions to scientific problems, or to analyze events and identify their causes (Rajasekar et al., 2013).

*Conclusion:* The conclusive part sums up important results and provides recommendations for future work.

## 3.2 Data collection

### 3.2.1 Historical fish escape data

Access to a database on previous escapes was secured through conversations and agreement with Tor-Arne Helle. He is a senior advisor at the Norwegian Directorate of Fisheries with responsibilities within NYTEK, NS-9415 and escape of fish. The contact was established with assistance from Safetec Nordic AS, but they are not given access to the database. The database contains information on reported fish escapes in the period 2006 to 2015. It is further described and discussed in Section 4.1.

### 3.2.2 Relevant literature

The collection of relevant literature relies mainly upon databases available through the University of Tromsø or on sources which are open to the public. For instance, Science Direct and SINTEF's open-access reports provided relevant information utilized in this thesis. Several keywords were used, e.g. 'fish farm escape', 'causes for fish escape', 'consequences of fish escape', 'risk indicators', 'safety indicators', 'major accident risk', etc. However, data is also collected through books, the internet and external sources. More specifically, literature on marine fish farming is obtained through scientific journals, reports, webpages and books. Similar sources provide insight on critical factors and operations with particular risk of escape. This mapping of risk-influencing factors (RIFs) and causes for escapes also benefits from conversations with external sources and material received from a Norwegian fish farming company. Furthermore, the Norwegian Directorate of Fisheries' database on previous escapes, as well as their online database (2015a) concerning critical operations and escapes provides additional insights. Literature on risk indicators is primarily provided by Safetec Nordic AS. These data are a combination of confidential and open-access reports and is supplemented with additional data collection through online databases.



### 3.3 Research approach

This thesis relies upon different research methods and tools to answer its objectives. It involves both qualitative and quantitative data, and utilizes different methods in separate parts of the study.

#### 3.3.1 Approach for assessing historical fish escape data

Microsoft Excel is utilized in the assessment of the database on previous escapes provided by the Directorate of Fisheries. The database is first adjusted to fit with the thesis' scope and limitations, before the data is analyzed statistically and results are presented through charts and tables.

#### 3.3.2 Strategy for development of risk indicators

Figure 3.2 illustrates the research approach for developing a model with RIFs and indicators. The risk context is implicit to cover the escape of fish from marine fish farms and is not a part of the illustration. The research method is a strategic risk assessment as illustrated in the flow diagram in Figure 3.2. The indicators and factors are identified in loops, which are repeated until the risk of escape is sufficiently covered or one fails to provide new insights.

##### Identification of risk-influencing factors

The risk-influencing factors are identified based on literature reviews, brainstorming, data on previous escapes and material received from external sources. All factors should be significant in terms of risk, thus each factor is rated based on potential impact and likelihood of occurrence. An additional criterion is that the factors have the potential for change; indicators measure *changes* in risk level, which implies that factors not prone to changes are inappropriate in this study.

##### Identification of indicators

For each of the selected factors, it is attempted to identify suitable and appropriate indicators. The identification is based on literature reviews and brainstorming. A set of criteria should be taken into consideration in the process and the requirements suggested by Haugen et al. (2012) may provide a basis for identifying suitable indicators. Furthermore, if indicators only measure a fraction of a factor, a set of indicators may be applied in order to obtain satisfactory measurements. In such cases, there are additional requirements, and four evaluation criteria for sets of indicators are suggested by Haugen et al. (2012). All requirements for indicators are described in Section 2.2.2.

##### Model with RIFs and indicators

After acquiring a set of risk-influencing factors with associated indicators, the results are portrayed in a model. This model should illustrate how RIFs and indicators may influence each other. Furthermore, it is desired to investigate the possibility of verifying appropriate indicators by investigating what have caused previous escapes. To what extent this is possible depends upon the nature and structure of the database.

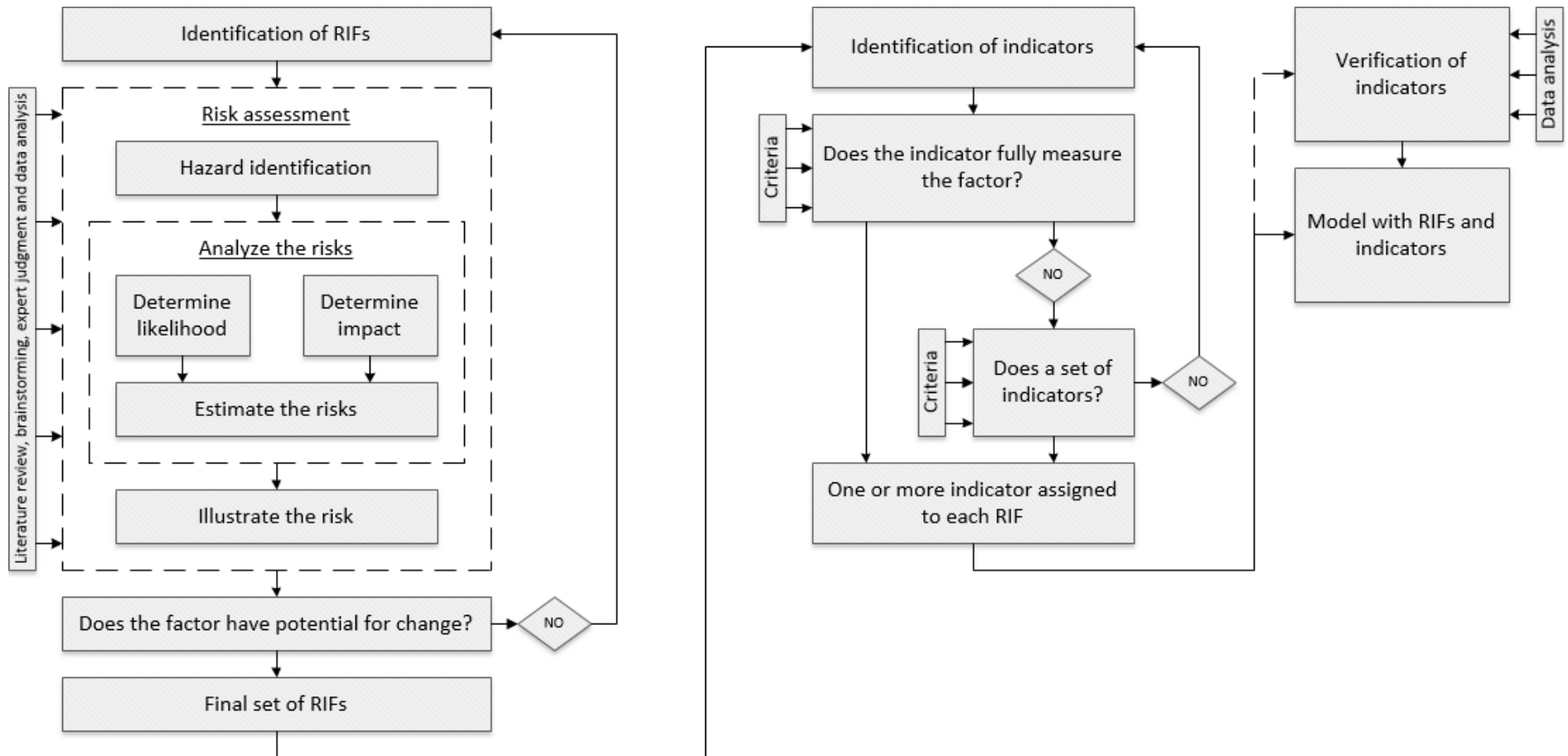


Figure 3.2: Research approach for developing indicators to monitor the risk of escape. Adapted from Ni et al. (2016), Haugen et al. (2012) and Øien and Sklet (2001b).

# Chapter 4

## Results and discussion

### 4.1 Method for data collection on fish escapes

By reviewing the current method for data collection on fish escapes, this section aims to discuss the first objective of the thesis. The reporting and processing of reported events is discussed, and the structure of the database is explained. The database is also corrected for minor discrepancies with respect to classification of certain parameters. Finally, particular limitations and challenges are discussed and some potential actions for improving the database are given.

#### 4.1.1 Reporting of events

Fish farmers are obligated to report any escapes or suspicion of escapes to the Directorate of Fisheries, regardless of whether the fish escaped from their own or from other production units (Akvakulturdriftsforskriften, 2011). After escapes are discovered, or in case of suspicions, fish farmers must immediately present an estimated number of escapees to the Directorate of Fisheries. The estimate is sent by either fax or email, but in cases where risk mitigation must be prioritized, initial reporting can be done by phone. However, a written report (part 1) must be submitted within 24 hours, and a final report (part 2) submitted within one week after the damage extent has been determined (Directorate of Fisheries, 2016c).

In addition to the initial reporting of an estimated number of escapees and an expected time for control of the fish cage, part 1 should give information on:

- Area of escape (hatchery, fish farm, transport, etc.)
- Plant specifics for fish farm
- Time of detection and an estimated time of occurrence
- Escape specifics (escapees, species, etc.)
- Fish health status
- Cause for escape
- Description of implemented measures to secure the remaining fish
- Information regarding recapture of fish
- Description of implemented measures to prevent repeating failures

- A sketch indicating where the escape originated

The final report (part 2) states any deviations from what was reported in part 1 and the final details regarding the extent of the escape. It furthermore asks for what measures have been implemented to prevent similar events and what number of fish has been recaptured. Together with part 1, the final report is submitted to the Directorate of Fisheries and further forwarded to the aquaculture escape commission (Directorate of Fisheries, 2016c).

### 4.1.2 Processing of reported escapes

The Directorate of Fisheries have internal procedures for follow-up on reported events. In most cases, the Directorate perform independent evaluations of escapes. Reports from these evaluations and the fish farmers' own investigations provide the grounds for determining the course of events. The teams responsible for evaluating the events consists of personnel with experience from the industry and relevant fields. To ensure appropriate and consistent categorization of events, the Directorate of Fisheries prioritize consistency when selecting the teams. All reported escapes are finally collected in a database and posted to the Directorate of Fisheries own website. However, causes for escapes and the ruling of guilt is withheld from the public. The database contains causes for escapes and other metadata, and is utilized by identifying repeating failures through statistical assessments. Areas that appear as particularly critical are prioritized when selecting future supervision efforts.

### 4.1.3 Structure of the database

The database contains information on reported escapes from 2006. It involves events concerning salmon, trout, rainbow trout, cod, lumpfish and halibut. Furthermore, it contains a number of causes and categorizations for escapes. It also gives information on time, location, farm type, farm size and net depth for each event, in addition to a comment section where the Directorate of Fisheries can leave their input on the nature of the escape. It furthermore provides general metadata concerning each event.

#### Classification of parameters

Escapes are classified as either 'small', 'medium' or 'large', depending on the number of escapees in each event. The intervals are given, but some efforts are required to correct mistakes where events are categorized incorrectly. The parameters 'farm size' and 'net depth' are classified in a similar manner, but the intervals are unknown and events are classified inconsistently throughout the database. By manually evaluating the data, a 'best fit' set of intervals are decided upon and given in Table 4.1.

Table 4.1: Classification intervals for parameters (a) number of escapees, (b) size of fish farm and (c) depth of net.

(a)		(b)		(c)	
Rank	Escapees	Rank	Perimeter (m)	Rank	Depth (m)
Small	$\leq 1000$	Small	$\leq 95$	Shallow	$\leq 15$
Medium	1001 - 10000	Medium	96 - 129	Medium	16 - 30
Large	$\geq 10001$	Large	$\geq 130$	Deep	$\geq 31$

In general, effort is put into making the database more ‘user friendly’. Classifications are made automatic and consistent throughout the database.

### Categorization of events

The categorization of events follows a predetermined and fixed set of areas, components and causes. This implies that if an area is first selected, the event must be categorized as one of the components within that area. The same logic applies for components and causes. Furthermore, each event is also categorized in an overlying category. These are:

- External causes
- Unresolved
- Not relevant
- Operational causes
- Structural causes

External causes are events imposed by external factors, for instance related to external boat activity, damage from predators or colliding flotsam. Unresolved events are not possible to connect to any of the categories, and the category ‘Not relevant’ are events which are not relevant to categorize. Operational causes are events happening during operations, e.g. damage from interactions with net or sinker tube. Structural causes are events with a structural origin, which may be related to failure of equipment or interactions between components. Furthermore, the database has four main areas for categorization:

- Fish farm
- Onshore hatchery
- Harvesting plant
- Transport of fish
- Unknown

The events categorized as unknown may be related to suspicions of escape or be events that are not sensible to categorize. A short description of the other categorization areas are given below. Most of the underlying components are self-explanatory, are previously mentioned in Section 2.1, or are discussed in later sections.

*Fish farm* is associated with escapes happening in direct association with the fish farm itself. The underlying components are ‘floating collar’, ‘net’, ‘fleet’, ‘boat’, ‘extra equipment’ and ‘miscellaneous’.

*Onshore hatchery* is associated with escapes from onshore plants. The underlying components are ‘tank’ and ‘pipe’.

*Harvesting plant* is not associated with the processing of slaughtered fish, but rather with escapes happening during delivery of fish to harvest. The underlying components are ‘floating collar’, ‘net’, ‘extra equipment’ and ‘transport equipment’.

*Transport of fish* is associated with escapes occurring during transport of fish. The underlying causes are ‘wellboat’ and ‘towing’.

#### 4.1.4 Limitations and potential improvements

##### Limitations and challenges

The database on previous escapes can be a valuable asset when preventing or mitigating the escape of fish. Knowing what have caused escapes in the past can provide vital insights on where supervision efforts and focus are needed. However, inconsistent categorization may significantly affect the results of any statistical assessment based on the database. This is particularly critical with respect to the number of escapees associated with a specific cause, as the number of escaped fish per year is often governed by maybe one or two major events. In general, it is essential that events are categorized consistently for the data to represent the actual causal picture.

After assessing the database, five influences with potential for reducing validity and/or usefulness are identified. These are:

1. Insufficient information on events
2. Variation in caseworkers
3. Lack of updating
4. Simple and unnecessary errors
5. Little information on underlying causes

Several events are categorized without sufficient information on the chain of events. This is evident from the comment section, sometimes describing ‘this is only suspicion...’, ‘it could also be...’ or similar. This lack of information may be a result of improper reporting of events, or be caused by uncertainties regarding the chain of events. Because escapes may be affected by a number of factors, it can be a challenge to determine a ‘main’ cause for escapes. Furthermore, it is unlikely that all past escapes have been reported. Consequently, there may exist causes and important factors with influence on escape that the database does not cover. Additionally, it is possible that fish farmers in the past have tampered with reporting to reduce both financial and societal consequences. There are also cases where certain parameters, e.g. net depth or farm size, are left blank or marked ‘unknown’. Most of these cases are related to e.g. transport of fish, where such parameters are irrelevant. However, there are escapes from fish farms that lack information on similar parameters.

The Directorate of Fisheries follow a fixed approach for categorizing the reported events. However, the proper classification for an event is not always obvious, and caseworkers may end up categorizing similar events differently. Hence, consistency in the teams responsible for categorizing events is important. This is also emphasized by the Directorate of Fisheries. Furthermore, the database contains reported escapes from 2006-2015, and there has likely been some development in how events are categorized during this period. Hence, it is important to update the database, such that events from 2006 and 2015 are categorized according to the same guidelines.

One example of a simple and unnecessary mistake is a series of events categorized as ‘transport of fish’, ‘wellboat’ and ‘handling’ (area, component and cause). According to the Directorate of Fisheries’ own classification form, no such categorization exists. The correct categorization is likely ‘transport of fish’, ‘wellboat’ and ‘handling of fish’. Simple

errors like that should be avoided because they give a wrong impression of how causes are distributed.

Furthermore, there are other examples of categorization ‘errors’ that contribute in reducing the validity of the results. These are not directly mistakes, but cases with discrepancies between categorization and information available in the comment section. Take, for instance, an event categorized under ‘fish farm’, ‘floating collar’ and ‘net-bag’. The event had more than 300 000 escapees, and according to the comment section, it was a seal that made a tear in the net. Hence, it is arguable that the event should have been categorized as ‘predator’ instead.

Underlying causes can be important for future work on preventing escapes. In its current format, the database provides little information on influencing factors. One example is a ‘net-bag’-event, which is described to be influenced by weather and icing, causing the cage to sink low enough for 12 200 fish to escape. However, without the comment section, the cause for escape would only be associated with ‘net bag’. The comment section does provide useful information on several events, but the information must be extracted manually. Additionally, there are cases with discrepancies between the comment section and the categorization. This creates uncertainties regarding what is the correct cause for escape.

### Potential actions for improvement

A categorization system that accounts for influencing factors and underlying causes could potentially improve the usefulness of the database. Additionally, there may perhaps be better ways of categorizing events. For instance, it may be worth considering the mort collection system and cleaning equipment as separate components with underlying causes instead of causes under the component ‘extra equipment’. Additionally, including a column specifying which operation incidents occur under, may help in highlighting particularly risky operations. However, a potential rework should involve personnel with fish farming experience, as well as researchers and other experts. In general, it is important that the database is both informative, reliable, easy to comprehend and allows for smooth extraction of statistical data to be used for risk assessment purposes.

In its current form, it is recommended to ensure consistent categorization of events to increase the validity of the database. Potential actions are:

- Correct for simple mistakes and errors
- A complete review of the database by going through old site-reports, preferably performed by one team to ensure consistency

For further improvement of usefulness with respect to risk assessment purposes, it is recommended to:

- Review the current approach for categorization of events
- Implement measures to include underlying causes for escapes
- Make the database available to fish farmers, researchers, etc. so it may be utilized in greater scale in reducing escapes from marine fish farms

An additional action could be to cooperate with the industry regarding reporting of near misses. Companies have their own internal systems, but there are no formal data collection on near misses on a nationwide scale. The number of near misses is likely far greater than the number of actual escapes, and systematizing them in a joint database could serve as an asset in developing measures to prevent future escapes. However, it is possible that this work is too extensive and best left at a smaller scale.

## 4.2 Investigation of causes for fish escape

To investigate what have caused fish escapes in the past, the thesis utilizes the Directorate of Fisheries' database on previous escapes. Thus, by assessing the database, this section aims to discuss the second objective of this thesis.

### 4.2.1 Scope of assessment

The Directorate of Fisheries' database on previous escapes is quite extensive and contains 672 events before any manipulation of the data is attempted. However, because fish farmers are required to report suspicion of escapes, the data consists partly of events with zero escapees. Certain events are considered irrelevant with respect to the analysis and are removed from the database. These are:

- events of suspicion;
- events which are recaptures and not real escapes;
- escapes from onshore hatcheries or freshwater farms; and
- escapes concerning either halibut or lumpfish

The database is reduced to 356 reported events. The remaining events provide the foundation for investigating for particular causes/parameters and escape of fish. The distribution of these events is shown in Figure 4.1.

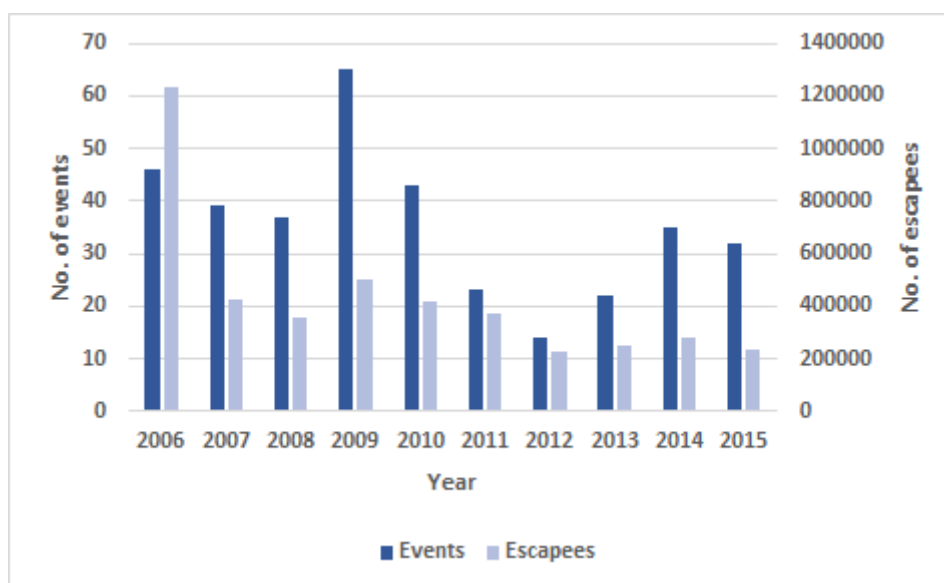


Figure 4.1: Number of events and escapees in the period 2006-2015



Table 4.2 shows how the 356 events and 4 307 127 escapees are divided on species and size of escapes. It is evident that a significant amount of the escapes is from salmon farms and that large escapes account for the majority of the escaped fish.

Table 4.2: Data basis divided by (a) species and (b) size of escape.

(a)			(b)		
Species	Events	Escapees	Size of escape	Events	Escapees
Cod	95	1 120 549	Small	200	46 573
Rainbow trout	29	472 078	Medium	75	322 191
Salmon	232	2 714 500	Large	81	3 938 363
Sum	356	4 307 127	Sum	356	4 307 127

Cod is treated separately because of behavioral differences and their deliberate attempts to escape through holes in the net (Aas and Midling, 2005). Salmon and rainbow trout however, are treated together. Information on fish sizes is available from 2010, but is not considered in the assessment. Furthermore, one trout-event with five escapees is included within the 29 rainbow trout events.

It may be argued that the number of escapees is a better measure of consequence than the number of events. The likelihood of influencing wild populations increases with an increased amount of escaped fish. However, even small events can induce negative consequences for personnel, company and industry. Furthermore, apart from special cases like escapes during lice testing, only minor differences in the course of events may be what separates small- and relatively large escapes. In other words, an escape of 10 000 fish can have the same cause as an escape of 100 fish. Hence, it may still be of interest to focus on causes for frequent escapes, even if these not necessarily are responsible for a high number of escapees. However, both are important and should be considered in the assessment.

### 4.2.2 Parameter assessment

The database is analyzed to check for correlation between a set of parameters and reported escapes. For certain parameters, it seems more appropriate to emphasize the number of events, and not the amount of escaped fish. The parameter assessment includes all species and investigates the following parameters:

- Month of escape
- Location of escape
- Construction type
- Size of farm
- Depth of net

### Parameter I: Month of escape

Table 4.3 illustrates how the 356 events are divided by months. Assessing the month of escape may be interesting as to reveal if certain seasons experience significantly more events than others do. Checking the month-escape distribution against companies' planning of critical operations as well as the frequency and location of moderate storms could potentially reveal interesting correlations.

Table 4.3: The 356 events sorted by month

Month	No. of events	No. of escapees	Avg. no. of escapees per event
January	39	1 152 593	29 554
February	17	282 923	16 643
March	17	372 588	21 917
April	16	438 264	27 392
May	22	152 198	6 918
June	26	114 619	4 408
July	24	77 299	3 221
August	33	129 278	3 918
September	46	316 860	6 888
October	45	371 199	8 249
November	45	688 712	15 305
December	26	210 594	8 100

Some tendencies are evident when looking at how the events are distributed on the different months. It appears that escapes are more common in the autumn, while the late winter months have significant lower amounts of escapes. In fact, the period from September to November represents roughly 39 % of the total number of reported events. However, looking at the average number of escapees per event, none of the mentioned months are even within the top 4. The months with the least reported events are actually among the top months in terms of number of escapees. However, the total number of escapees during a year are sometimes governed by maybe one or two major events.

### Parameter II: Location of escape

Figure 4.2 illustrates how the events are divided by location of occurrence. It is clear that Hordaland, Møre og Romsdal and Nordland represent the counties with the highest number of reported events. The situation changes slightly when considering the number of escapees, with Troms entering in the top 3. However, these data provide little insight on the risk of escape and should be compared with the prevalence of fish farms amongst Norwegian counties.

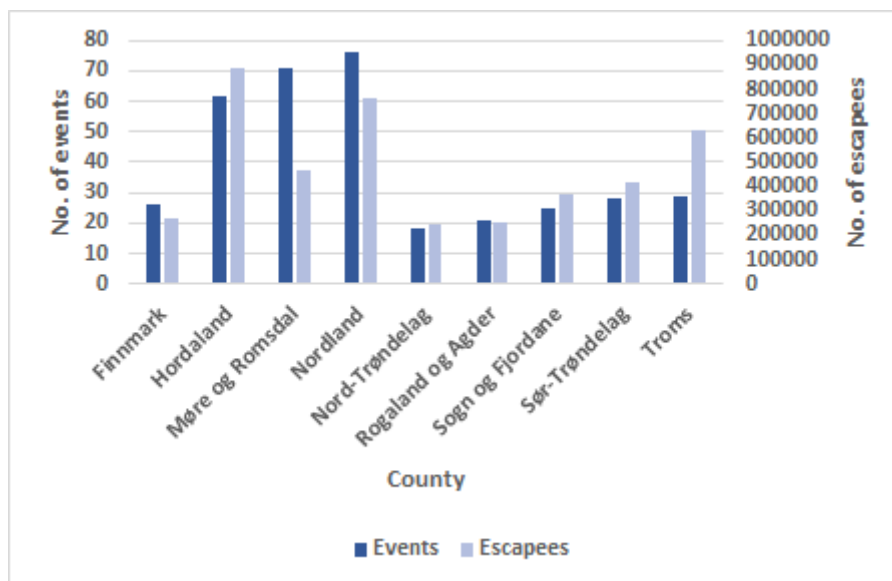


Figure 4.2: Reported escapes sorted by location.

The Directorate of Fisheries (2016b) online database on biomass statistics provides information on how fish farms are distributed amongst the different counties. However, as the escape-data ranges from 2006 to 2015, the numbers in Table 4.4 are averaged data from the same period. Furthermore, the data is given only for salmon- and trout farms, but is believed to provide a satisfactory picture of the total distribution of fish farms in Norway.

Table 4.4: Distribution of Norwegian fish farms by location.

County	Number of farms	%
Finnmark	249	6,7
Hordaland	727	19,6
Møre og Romsdal	359	9,7
Nordland	791	21,3
Nord-Trøndelag	232	6,2
Rogaland og Agder	335	9,0
Sogn og Fjordane	321	8,6
Sør-Trøndelag	306	8,2
Troms	394	10,6
Sum	3714	100

By combining data from Figure 4.2 and Table 4.4, a relative frequency of escape is estimated, Figure 4.3. The figure illustrates in what county escapes are most likely to happen, taking into account the fish farm distribution and the number of reported events in each county.

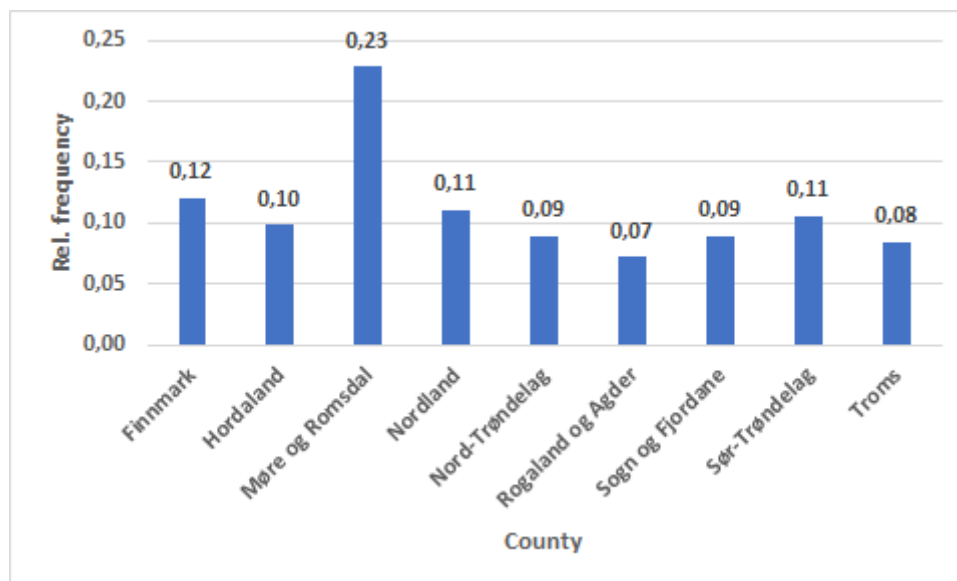


Figure 4.3: Relative frequency of escape.

While Nordland has the most reported escapes, it is less critical in terms of escapes per farm. Relative speaking, it is still among the top three counties, but it is significantly bypassed by Møre og Romsdal. However, it should be stated that, while Møre og Romsdal accounts for 20 % of the total number of events, it is only responsible for 10.8 % of the escaped fish. On the other hand, Finnmark is ranked as no. 6 with respect to the number of escapes, but appears as the second most critical county when accounting for the number of fish farms in each county.

### Parameter III: Farm type

The results in Table 4.5 indicate that 51 % of the reported escapes are from fish farms with plastic constructions. However, the results are not representative without supplementary data, i.e. information on the general distribution of construction types amongst Norwegian fish farms. Unfortunately, the author has not succeeded in obtaining such data.

Table 4.5: Escapes sorted by farm type.

Construction type	No. of events	%
Steel	94	26.4
Plastic	182	51.1
Unknown	80	22.5

The high number of unknown farm types are either related to escapes without direct associations with the net/cage (e.g. escapes during transport of fish), or because the database lacks information on certain events.

### Parameter IV: Farm size

The farm size (perimeter, m) is classified as either small ( $\leq 95$ ), medium (96 - 129) or large ( $\geq 130$ ). However, the database provided no information on the ranking-intervals,

thus the classifications are a set of ‘best fit’ intervals decided by the author. The result of the farm size assessment is illustrated in Table 4.6 below.

Table 4.6: Escapes sorted by farm size.

Perimeter	No. of events	%
Small	138	38.8
Medium	57	16.0
Large	61	17.1
Unknown	100	28.1

Most escapes are from ‘small’ fish farms, but there is a lack of supplementary data regarding the general situation in Norway. Additionally, the size-classification intervals should correspond with how it is standardized in the industry to provide more comparable results.

### Parameter V: Net depth

Table 4.7 illustrates how escapes are divided on the different net depths. The nets are either shallow ( $\leq 15$ ), medium (16 - 30) or deep ( $\geq 31$ ), based on the author’s best judgment. The results are considered to provide little or no indication on what net depths are most critical without being supplemented with additional data.

Table 4.7: Escapes sorted by net depth.

Net depth	No. of events	%
Shallow	154	43.2
Medium	70	19.7
Deep	23	6.5
Unknown	109	30.6

### 4.2.3 Assessment of causes for previous escapes

The cause assessment is conducted according to the limitations described in the introduction to this section. First, the distribution of events on overlying areas and categories is presented, before a series of charts and tables are utilized to highlight more specific causes for previous escapes.

#### Overlying areas and categories

From Table 4.8 it is evident that the main bulk of the escapes are from the fish farm itself. It is also the most dominant area with respect to the number of escapees per event. This applies for all species, and especially for cod where the other areas are significantly less prominent. A fair share of the salmon/trout events are from other areas, but the number of escapees per event in these areas are significantly lower. This is not considering the unknown area, which consist mainly of one event where a trawler hooked in the mooring system.

Table 4.8: Distribution of events by area

Area	Salmon/trout		Cod		Combined	
	Events	Escapees	Events	Escapees	Events	Escapees
Fish farm	187	2 995 671	90	1 101 637	277	4 097 308
Harvesting plant	29	52 472	2	7 980	31	60 452
Transport of fish	41	36 483	2	9 932	43	46 415
Unknown	4	101 952	1	1 000	5	102 952
Sum	261	3 186 578	95	1 120 549	356	4 307 127

The distribution of events on overlying categories is shown in Table 4.9. For salmon/trout, the main bulk of escapes are of an operational origin. However, structural failures account for the highest number of escapees, while external causes are most significant in terms of escapees per event. For cod, structural failure is most significant with respect to both the number of events and the amount of escaped fish. However, external causes are also here most critical in terms of escapees per event.

Table 4.9: Distribution of events by category

Category	Salmon/trout		Cod		Combined	
	Events	Escapees	Events	Escapees	Events	Escapees
External	20	625 274	13	314 944	33	940 218
Unresolved	16	53 787	6	79 110	22	132 897
Not relevant	9	31 836	3	4 008	12	35 844
Operational	139	1 041 461	11	101 119	150	1 142 580
Structural	77	1 434 220	62	621 368	139	2 055 588
Sum	261	3 186 578	95	1 120 549	356	4 307 127

### Components and causes

Figure 4.4 illustrates the most frequent causes for escape of salmon and trout from Norwegian fish farms. As the database involves a number of less frequent causes, all causes associated with less than five events are merged into the factor ‘other causes’. This pool includes events that were already categorized as ‘miscellaneous’ as well. However, few events do not necessarily imply few escapees, which illustrates the challenge of emphasizing the number of events or the size of escapes.

Events categorized as ‘handling’ are operational escapes. They account for a large portion of the events and are often escapes associated with net interactions. Crowding of fish and raising of net are more specific operations that are mentioned. However, many different causes are described in the comment section and ‘handling’ appears as a relatively wide category for escapes. Furthermore, escapes associated with the sinker tube are often related to interactions between sinker tube, net and chains. Few specific reasons for interactions are mentioned, but potential causes may be raising, lowering and improper attachment of the net. Unfavorable sea conditions increase the risk as well.

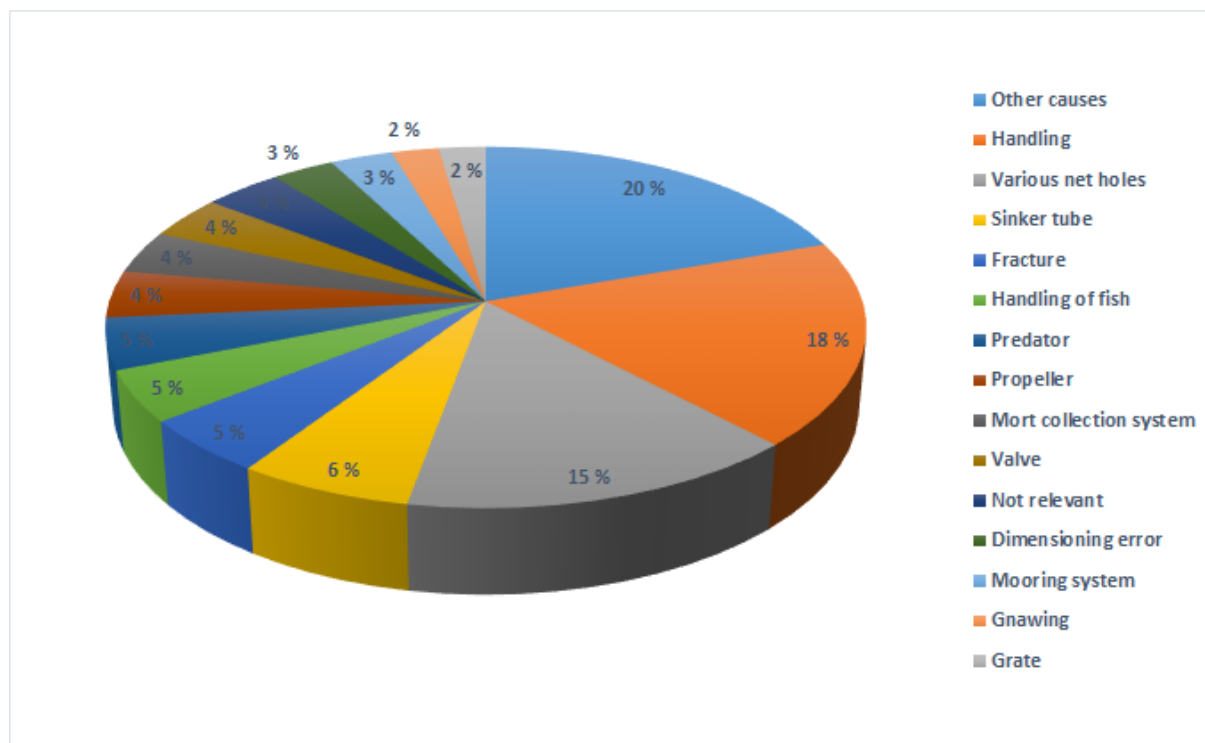


Figure 4.4: The most frequent causes for escape of salmon and trout.

The top five causes with respect to number of escapes are shown in Table 4.10 (a). As in Figure 4.4, it is evident that several of the most frequent factors are not related to any specific cause. ‘Various net holes’ may imply that the fish have been pushed out of the net during crowding, but the reason for net damage is unknown. Miscellaneous events are related to many different components/areas, and some events could potentially be categorized more specifically. Fractures are related to pumping equipment and happen when harvest-ready fish is transported to the plant. Broken pipe connections and screen boxes are typical causes for escapes during pumping of fish. However, these mistakes/failures are easier to detect and mitigate than escapes through e.g. underwater net-tears. Consequently, ‘fracture’ is not among the top five causes with respect to the average number of escapees, Table 4.10 (b).

Table 4.10: Top five causes for salmon and trout escapes with respect to (a) the number of events and (b) the average number of escapees

(a)		(b)	
Cause	No. of events	Cause	Avg. no. of escapees
Handling	48	Net bag	138 638
Various net holes	39	Net attachment	44 805
Miscellaneous	17	General overload	38 123
Sinker tube	17	Sinker tube	29 063
Fracture	13	Cleaning	27 366

With respect to the number of escapees per event, ‘net bag’ is by far the most dominant cause. However, this factor is a bit ambiguous and not related to any specific cause.

Additional causes with more than 20 000 escapees in average are ‘dimensioning error’ and ‘environmental forces’. However, of the top causes, only ‘dimensioning error’ and ‘sinker tube’ are associated with more than five events.

The distribution of escapes by components is given in Table 4.11. The ‘wellboat’ events do not justify the risk associated with wellboat operations. This component is related to the transport of fish, but other components involves incidents concerning wellboats as well. For instance, many of the events related to transport equipment are escapes happening during pumping of fish with wellboats. Additionally, the component ‘boat’ involves accidents with wellboats, while damages to either floating collar or net may also be associated with wellboat operations.

Table 4.11: Distribution of events by component

Component	Salmon/trout		Cod		Combined	
	Events	Escapees	Events	Escapees	Events	Escapees
Other factors	10	3 837	-	-	10	3 837
Wellboat	39	23 168	2	9 932	41	33 100
Boat	17	80 927	2	198 280	19	279 207
Extra equipment	25	291 987	7	54 758	32	346 745
Floating collar	20	983 319	5	199 587	25	1 182 906
Fleet	1	60 528	-	-	1	60 528
Not relevant	10	122 788	3	4 008	13	126 796
Net	121	1 605 151	76	653 984	197	2 259 135
Towing	2	13 315	-	-	2	13 315
Transport equipment	16	1 558	-	-	16	1 558
Sum	261	3 186 578	95	1 120 549	356	4 307 127

The high number of cod-escapes related to ‘net’ is a result of the cod’s deliberate attempts to escape by biting holes in the net. This is illustrated in Figure 4.5, where it is evident that fish biting is the most dominant cause for cod escapes. Predators and various net holes appear as other dominant causes, and together they account for 74 % of the total number of reported cod escapes. However, the number of cod farms has decreased in recent years, and not a single fish-biting event was reported in 2014 or 2015.



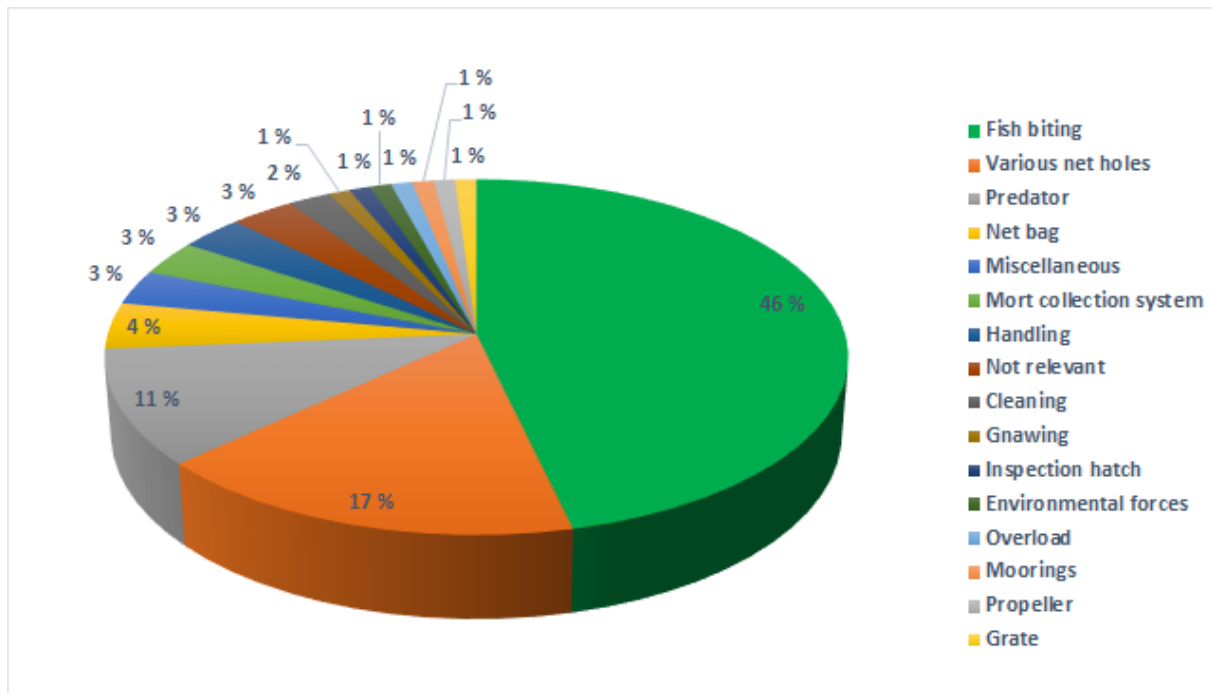


Figure 4.5: The most frequent causes for escape of cod

The complete overview of cod escapes is given in Table 4.12. Several of the less frequent causes are associated with a significant amount of escaped fish. ‘Various net holes’ for instance, have fewer events than ‘fish biting’, but is significantly more critical in terms of the amount of escaped fish. However, because it is associated with a number of different factors, it is hard to point at specific causes. In fact, the comment section reveals that these events are often suspected to be related to either fish biting or predators.

Table 4.12: Complete overview of the reported cod escapes

Cause	No. of events	No. of escapees	Avg. no. of escapees per event
Fish biting	44	175 711	3 993
Various net holes	16	307 578	19 224
Predator	10	132 275	13 228
Net bag	4	196 587	49 147
Miscellaneous	3	38 540	12 847
Mort collection system	3	21 172	7 057
Handling	3	2 580	860
Not relevant	3	4 008	1 336
Cleaning	2	3 050	1 525
Gnawing	1	15 000	15 000
Inspection hatch	1	9 832	9 832
Environmental forces	1	300	300
Overload	1	15 536	15 536
Mooring	1	173 026	173 026
Propeller	1	25 254	25 254
Grate	1	100	100
Sum	95	1 120 549	11 795

The cause ‘mooring’ counts only one event, but represents more than 15 % of the escaped cod. However, the high uncertainty related to the categorization of this event makes it challenging to justify labeling it as a critical cause for escape. It is categorized under ‘boat’ and ‘mooring’, but the comment section describes it as either flotsam or sinker tube. Unfortunately, this sort of uncertainty is prevalent on several occasions in the database and puts limitations on the validity of the results.

#### 4.2.4 Some final remarks

The parameter assessment showed some tendencies, but the results must be backed by supplementary data to provide grounds for conclusion. Additionally, it is important to consider the actual causes for escape in combination with the parameters.

There are significant differences in the degree of severity of events. The ten largest escapes account for more than 34 % of the escapees, and the number of escaped fish per year is often governed by one or two major events. Furthermore, the major events one year are not necessarily an indication of what will cause a major event the next year. Additionally, large escapes may originate from similar causes as smaller events, thus the causes for minor escapes should not be ignored.

Interactions between sinker tube and net is one of the most critical causes for previous escapes. Handling of net and other components are other critical activities which have led to escapes in the past. Such activities may be performed in association with larger operations, e.g. delousing of fish. Wellboat operations also illustrates particular risk of escape. Fish biting is the most dominant cause for cod escapes. It is associated with three major events of 30 000, 36 000 and 46 000 escapees, and despite being responsible for merely 16 % of the escapes fish, fish biting still has potential for major accidents.

The data analysis is in large parts reliant upon the categorization of events as performed by the Directorate of Fisheries. Unfortunately, the database is prone to uncertainties with respect to the categorization of events, which limits the validity of the results. For the record, some obvious mistakes have been corrected, but without access to actual site reports, the author feels it is not justified to perform any large-scale updating of the database.

### 4.3 Development of risk indicators

This section aims to discuss the third objective of this thesis, but provides additional insights on particular causes for escapes as well, i.e. research objective two. By utilizing the concept of risk indicators it is attempted to develop a means for monitoring changes in risk of escape from marine fish farms. The underlying principle is that changes in risk-influencing factors represent a change in the risk of escape. However, such factors are not always directly measurable, thus indicators are developed as tools for measuring the state of RIFs. This is achieved through periodic measurements of indicator values, which allows safety and risk analysts to analyze and assess deviations in the risk level. To the author’s best knowledge no similar work has been done focusing on implementation of risk indicators on fish farming and fish escape. In this regard, the present work, in analogy with oil and gas and processing industry, develops a methodology for identifying

RIFs and then suggests a number of indicators to measure the state of such RIFs.

### 4.3.1 Identification of risk-influencing factors

This section aims to identify risk-influencing factors as a basis for developing risk indicators. A preliminary risk analysis (PRA) is utilized for this purpose, and the procedure is adapted from USCG (2001).

#### Introduction to PRA

According to the assessment of previous fish escapes in Section 4.2, similar scenarios may lead to different consequences. This creates a challenge when ranking the different hazard in terms of risk of escape. To cope with this challenge, a preliminary risk analysis is utilized. The advantage is that the potential consequences may be divided into three degrees of severity, illustrated in Table 4.13. Thus, it is possible to account for the variations in consequence from similar hazards.

Table 4.13: Consequence scoring categories.

Description	Score	Escapees
Minor	1	1 - 1000
Moderate	2	1001 - 10000
Major	3	>10000

The effects on wild populations, economics and loss of reputation following fish escapes are not easily determined. Hence, the number of escapees is used as a measure of consequence. However, with increasing number of escapees, the risk towards the mentioned factors increase as well.

Hazards are given a likelihood of occurrence for each of the different severities. The Directorate of Fisheries' database on previous escapes provides the basis for determining appropriate frequencies, and the selected frequency scoring intervals are given in Figure 4.6. The intervals are adapted from USCG (2001) to correspond with the frequency-span of the reported escapes in the database.

The confidence of the frequency scores assessment is given in a separate column in the PRA table. The confidence level is either low, medium or high, depending on the certainty of the appointed frequencies:

- High: High certainty in the available data. Confident that all event-categorizations correspond with the actual causes for escape.
- Medium: Medium certainty in the available data. Some uncertainties if all event-categorizations correspond with the actual causes for escape.
- Low: Low certainty in the available data. Great uncertainties if all event-categorizations correspond with the actual causes for escape.

Assigning certainty levels to each frequency scoring allows for better risk estimates. For instance, a medium-risk hazard with high certainty may be as- or more important than

Frequency Score Descriptions	Frequency Scores
<b>Extreme</b> (More than 20 times per year)	<b>5</b> 20/y
<b>Very frequent</b> (5 to 20 times per year)	<b>4</b> 5/y
<b>Frequent</b> (1 to 5 times per year)	<b>3</b> 1/y
<b>Occasional</b> (one time every 1 to 5 years)	<b>2</b> 0.5/y
<b>Rare</b> (one time every 5 to 10 years)	<b>1</b> 0.1/y
<b>Remote</b> (Less than one time per 10 years)	<b>0</b>

Figure 4.6: Frequency scoring categories. Adapted from USCG (2001).

a high-risk hazard with low certainty. Finally, the frequency and severity is combined to express the risk of escape. This is done through a risk index number (RIN), which makes it possible to rank the different hazards relative to each other. The risk index number is adapted from USCG (2001) and given in Equation 4.1.

$$RIN = \frac{(F \times C)_{Hazard\ category\ 1} + (F \times C)_{Hazard\ category\ 2} + (F \times C)_{Hazard\ category\ 3}}{100} \quad (4.1)$$

Where

- F is the average frequency of the hazard (events per year); and
- C is the average consequence of the hazard (escapes per event)

An index number of 100 is chosen to express the RIN in a convenient magnitude. Average numbers are used both for frequency and consequence when calculating the risk index number. This means that the representative frequency is the midpoint between the upper and the lower bounds of the frequency ranking in Figure 4.6. Likewise, the representative consequence is the middle point of the consequence classification intervals in Table 4.13. However, the representative consequence for ‘major’ is set to 50 000, and the representative frequency for score ‘0’ and ‘5’ is set to 0.055 and 35, respectively.

### Hazard identification

Escapes can be influenced by a number of factors, and it is not always obvious what specifically caused the escape. Hence, selecting one specific factor as the cause for an escape may be challenging. However, causes for the escape of fish may be sorted in three overlying categories:

- Escape due to net failure (hole/tear)
- Escape due to cage breakdown
- Direct escape

Fish escapes are most common through net tears or holes in the net, but may also occur due to a complete or partial breakdown of the farm construction. In addition, direct escapes can happen during lice tests, pumping of fish or in form of smolt-leakage, amongst others. However, one cause may result in both net failure and cage breakdown, making it a challenge to categorize escapes accordingly. Nevertheless, below follows a short description of factors, operations and systems with influence on the risk of escape.

#### ***Sabotage***

Human interference through sport fishing or pure sabotage on net/cage can result in unwanted escapes. For instance, severe sabotage caused 100 000 fish to escape from a farm in Kåfjorden in Alta in 2005 (NRK, 2005). The saboteurs had cut off attachment ropes causing the net to sink.

#### ***Earthquakes and rock- and mudslides***

Earthquakes, rock- and mudslides have the potential for generating tsunami waves that can severely damage fish farms. Slides may in addition present a hazard in form of direct impact.

#### ***High 'density' of fish farms***

With several fish farms in immediate proximity of each other, the potential consequence of an accident increases. If one cage is damaged by e.g. flotsam, it can put additional loads on adjacent cages. Additionally, with combined mooring systems, several cages can be affected by a single mooring failure.

#### ***Weather impacts and rough sea state***

Weather conditions is critical as it both affects and complicates most operations. However, it may also present a more direct cause for escapes. In extreme cases, bad weather and sea state can tear off components and result in complete breakdown of fish farms. It can also induce wear between various components and net, ending in tears or holes with subsequent escapes. Additionally, drift ice may present a hazard for the northernmost areas in Norway.

#### ***Icing***

Severe icing is critical as it can cause the cage to sink. It may also induce fracture of railings and result in extra loads on the net. Additionally, sharp edges on broken components can tear holes in the net.

#### ***Flotsam***

Storms and bad weather can induce severe damage to coastal constructions. This presents a risk towards marine fish farms as torn off objects may drift and damage nets and/or cage constructions. Especially large flotsam are challenging to prepare for, as they can induce very large loads that fish farms are not able to withstand.

### ***Algae growth***

Algae growth is critical with respect to mainly two factors. First, loads on the net is increased by fouling, and second; a clogged up net reduces the oxygen level in the cage. The latter pose a risk towards fish mortality with subsequent risk of net tears and attraction of predators. Additionally, a heavier net may require rougher use of lifting equipment, increasing the risk of net tears. Furthermore, algae growth may increase cleaning efforts, which in turn increase the wear on nets.

### ***Predators***

Predators are attracted to fish farms, and it is important to do proper area assessments before selecting locations for fish farming. Furthermore, it is essential to pay attention to accumulation of dead fish to prevent predators from tearing up the net.

### ***Boat mooring and maneuvering***

It is important with sufficient lighting and marking of fish farms, especially in dark seasons. This is particularly important with respect to external vessels whom may not be familiar with the cages' position. This also applies for mooring systems, considering the potential risk of interaction with trawlers. Boat maneuvering is critical with respect to both direct collisions and interactions with propellers. In addition to net tears, propellers can interact with loose ropes and result in severe damage to the net. Furthermore, improper mooring onto fish farms can put uneven and unfortunate loads on the cage construction.

### ***Moorings and main components***

Main components are dimensioned according to the environmental forces the plant is expected to be exposed to. However, the dimensioning requirements depends on when, and for how long, measurements are taken. For instance, the current velocity is not constant and may differ depending on what season the measurements are taken. This is emphasized by Jensen (2006).

### ***Feeding system***

Temporary and improper attachment of the feeding system has been a contributing factor to previous escapes. Combined with bad weather, the rotor spreader can break off and interact with the net. Additionally, passing feeding hoses through the railing net can induce gnawing and wear on the net.

### ***Mort collection system***

The mort collection system is important as it prevents the accumulation of dead fish. However, improper positioning can result in insufficient mort collection and unfortunate net interactions. Raising of the system is critical as well, as unwanted interactions with the net may occur.

### ***Interactions between net and sinker tube***

Interactions between components may be induced and/or increased by improper net attachment, raising/lowering of net and strong currents. There are fish farms that utilize weights instead of sinker tube, but similar risks applies for these types of farms.

### ***Cleaning of nets***

Lack of cleaning can result in fouling of nets. Furthermore, cleaning equipment can dam-

age the net and should be inspected before use, in addition to constant monitoring during cleaning.

#### ***Interactions with net and sinker tube***

Many operations involve interactions with the net and sinker tube. All such activities present a risk of escape and must be performed with care. The use of lifting equipment, like strong cranes, is particularly risky, as operators may not notice a stuck net before it is too late. Furthermore, in larger operations there are several actors in play at the same time, which sets requirements for proper communication and cooperation, as well as thorough planning in advance.

#### ***Net attachment***

Improper attachment of nets can create uneven loading and result in net failure with subsequent escapes. This is particularly critical in cases where net loads are increased by environmental forces.

#### ***Lice tests***

Fish farmers perform periodic lice tests to assess the need for delousing. During such tests, there is a risk of fish escapes. However, the potential consequence is relatively low.

#### ***Dropping of objects***

Dropping sharp edged objects into the cage should be avoided as it can induce holes or tears in the net. This risk can be mitigated by assuring there are no loose objects in immediate proximity of the cage.

#### ***Smolt leakage***

Having fish farms with appropriate mesh sizes is essential when smolt is transferred to sea farms. However, some leakage may still occur because of potential differences in smolt sizes.

#### ***Fish biting***

Special case for cod where the fish deliberately tries to create and escape through holes in the net.

#### ***Crowding of fish***

Crowding of fish is an operation where the fish is forced into a restricted area, often performed to facilitate pumping of fish. If the net is damaged prior to this operation, there is a risk of 'pushing' the fish out of an existing hole. However, escapes may occur regardless of existing holes, as the operation itself presents a risk for net damage.

#### ***Delousing with tarpaulin***

During delousing of fish there is a risk of escape because the operation is complex, involves many actors and include frequent interactions with the net. Additionally, the setting of tarpaulin involves several workboats and is increasingly challenging if performed under bad weather conditions.

#### ***Loading and unloading of fish***

Loading and unloading of fish is associated with transport of fish between fish farm and

wellboat or harvesting plant. Related operations are sorting, splitting, transport and delousing of fish. Both pumping hoses, pipe connections, hatches, valves and screen boxes can fail and induce escapes. Additionally, there is risk associated with wellboat maneuvering.

#### ***Transport of fish***

Forgetting to close the hatch during transport of fish can result in escapes. There is also risk associated with boat maneuvering.

#### ***Towing operation***

As in all other use of boats, there is a risk of fish escapes related to collisions and propeller interacting with net or loose ropes. Sufficient lighting, navigation systems and radio communication should be applied to reduce the risk of escape. In addition, water depth and sea route with potential obstacles are to be assessed in advance. The towing speed must be adapted to the circumstances and in general be in accordance with guidelines and procedures for towing operations. In general, towing is considered to be a risky operation and is not practiced by all companies.

#### ***Maintenance and supervision efforts***

Poor supervision and maintenance can result in failure of equipment vital to prevent escapes. The net should be under close supervision to make sure it is attached correctly, sufficiently suspended and not subjected to any wear from chains, weights or sinker tube. Other components and the farm construction itself is of course also important. Electrical systems should also be under supervision to prevent fire or other hazards that can severely damage the construction.

#### ***Changing of nets***

Changing of nets is regarded as a risky operation. For instance, situations have occurred where the net ‘drops’ down and the fish is allowed to escape.

### **Risk ranking**

Table 4.14 presents the selected hazards and how they are assessed in terms of risk. The Directorate of Fisheries’ database on previous escapes is kept in mind when defining/structuring the hazards. This is done in order to acquire the best possible grounds for assigning frequency categories.

The method for quantifying risk significantly ‘favors’ major events. Consequently, hazards that are not associated with any major escapes receive relatively low risk index numbers. It has been argued that causes for minor events should not be ignored because they may have major accident potential. However, this is not always the case. Lice tests for instance, are limited to minor escapes and thus are not regarded as a significant threat. However, it is stressed that the risk ranking takes basis in the database on previous escapes, which is prone to certain limitations and challenges.



Table 4.14: Preliminary risk analysis

Code	Hazard	Frequency			Certainty	RIN
		1	2	3		
H-01	Sabotage	1	1	1	Low	168.00
H-02	Weather impacts and rough sea	1	2	3	Med	1542.76
H-03	Icing	0	1	2	Med	391.78
H-04	Flotsam	1	1	1	Med	168.00
H-05	Increased net weight (algae/fish mortality)	0	1	0	Med	44.28
H-06	Predators	3	2	2	Low	431.27
H-07	Boats	2	2	1	Med	195.01
H-08	Mooring system	1	1	2	Med	393.00
H-09	Interactions between net and feeding system	1	1	1	Med	168.00
H-10	Interactions between net and mort collector	2	1	1	Med	170.26
H-11	Interactions between net and sinker tube	2	1	3	Med	1520.26
H-12	Cleaning of nets	1	1	1	Med	168.00
H-13	Interactions with net (including attachment)	3	2	3	Low	1556.27
H-14	Lice tests	2	0	0	Med	34.28
H-15	Dropping of objects	0	0	1	Med	153.30
H-16	Smolt leakage	1	0	0	Med	32.03
H-17	Crowding of fish	1	1	1	Low	168.00
H-18	Delousing with tarpaulin	2	1	1	Low	170.26
H-19	Loading and unloading of fish	4	2	1	Low	253.82
H-20	Towing operation	0	1	1	Med	166.78
H-21	Transport of fish	1	1	0	Med	45.50
H-22	Fish biting (cod)	3	2	2	Low	431.27
H-23	Changing of nets	1	0	1	Med	154.53

Some of the previously mentioned hazards are excluded from the risk ranking. This is the case if they are not direct hazards or if the likelihood of occurrence is considered insignificant. Furthermore, not all hazards are directly comparable. For instance, interactions with net occur in many operations and this risk is not directly comparably with the risk associated with separate operations. However, it is included as a separate hazard in order to emphasize the criticality of net interactions.

‘Weather impacts and rough sea’ received a relatively high RIN and appears as one of the most significant hazards. However, weather conditions is not necessarily an actuating cause, but often a contributing factor which complicates all activities on the farm. A potential measure for reducing the direct impact from bad weather is proper dimensioning through thorough location assessments with respect to current velocity, wind speed, wave height, etc. Extreme weather is hard to fully prepare for, but avoiding quick fixes and temporarily solutions may reduce the risk of damaged and torn-off equipment. Furthermore, implementing a set of operational decision-parameters, similar to what is utilized within O&G, removes the uncertainty as to when operations should be postponed or stopped due to bad weather.

## **Organizational factors**

Researchers have argued that previous accidents in other industries could have been avoided with more pronounced focus on organizational factors. Such factors may be underlying causes that indirectly contribute to unwanted events. It is believed that by monitoring organizational aspects, one may be able to provide early warning signs of major accidents. To monitor the risk of escape from marine fish farms, five organizational factors are identified and described below. However, some of these may have technical and operational characteristics as well.

### ***Training and competence of personnel***

Experience is important and may serve as a measure of personnel's competence. However, fish farms are not necessarily operated equally and may have different degree of technology. It is preferred that operators have sufficient experience with the type of equipment they are expected to work with. Training of personnel is another important aspects, and new recruits should receive proper training and be given information regarding farm-specific guidelines and procedures. Competence of personnel hired from external companies, e.g. wellboat crews, is of equal importance.

### ***Procedures and SJA***

Every operation of a given degree of complexity should follow fixed procedures. It is important that these instructions are meaningful and adapted to the given location. Operators may be tempted to skip procedures if they are regarded as unnecessary or particularly time consuming. Additionally, critical operations should be performed following safety job analyzes (SJA). A SJA usually consist of a form where potential hazards, consequences and risk mitigating measures are described for each of the work tasks that are to be performed.

### ***Planning, organization and deviations***

When planning operations it is important to consider weather forecasts and the availability of external work forces which may be required. Proper coordination with other fish farming companies can increase the availability of e.g. wellboat crews and cleaning companies. Utilizing external companies that are familiar with the farm and its personnel can improve communications and cooperation. Furthermore, operators must be encouraged to report deviations and management should process these in an efficient manner. Frequent meetings between management and operating crews can assist in highlighting specific areas of concern. Additionally, it is important that the personnel responsible for procedures understand the situation 'out on the farm'. Furthermore, management should provide sufficient and competent staffing, as well as pay attention to the workload given to operation managers. Time pressure and overtime are other critical aspects.

### ***Inspection, maintenance and control***

The net should be inspected for holes or other damages both before and after critical operations. ROVs or divers may be utilized during inspection and control of the net.

### ***Design and technical condition***

The design life of the farm must be considered and the technical state should be reviewed at certain intervals. The technology level on the farm should be compared to the operators ability to adapt. Technology can make operations easier, but if workers do not know how to operate it properly, the risk of accidents may increase.

### 4.3.2 Selection of risk-influencing factors

Table 4.15 presents a set of risk-influencing factors as basis for identifying risk indicators. The identification is based on the evaluation and discussion in Section 4.3.1. However, some of the hazards are not listed as risk-influencing factors, while others are presented in a different format. This may be because they are regarded as low-risk hazards or as more direct causes for escapes. Furthermore, some factors are considered challenging to influence or is assumed to have little potential for change.

Table 4.15: Risk-influencing factors.

No.	Risk-influencing factor
1	Frequency of net interactions
2	Attachment of net
3	Performing of critical operations
4	Boat maneuvering
5	Accumulation of dead fish and attraction of predators
6	Dropping of objects
7	Training and competence of personnel
8	Procedures and SJA
9	Planning, organization and deviations
10	Inspection, maintenance and control
11	Design and technical condition

Weather and sea can damage fish farms and complicate farming operations. However, it is not possible to influence the occurrence of bad weather, and it is considered as more of an external influence. The importance of considering weather forecasts is included in planning of operations, and the dimensioning of fish farms to withstand environmental forces is part of the design. Fish biting is a critical factor, but the prevalence of cod farming is decreasing and it is considered hard to monitor the associated risk. In general, there are many factors with potential influence on escapes, but not all are suitable for developing indicators.

### 4.3.3 Identification of indicators

Table 4.16 presents a proposed set of indicators to monitor the risk of escape from marine fish farms. The indicators are listed under their respective RIFs and are categorized as either operational, technical or organizational, or a combination of these. The different types are abbreviated with op, tech and org, respectively. Operational indicators should measure the risk related to operations, e.g. associated with maintenance. Technical indicators should measure the state of technical devices implemented to prevent escapes, e.g. the cage. Organizational indicators measure the state of the organizational factors, e.g. level of competence on personnel.

Table 4.16: Proposed set of indicators to monitor the risk of escape.

No.	Indicator	Type	Reference
<i>Frequency of net interactions</i>			
1.1	Avg. number of daily interactions	Op/org	-
<i>Attachment of net</i>			
2.1	No. of near-misses and escapes	Op	-
<i>Performing of critical operations</i>			
3.1	No. of near-misses and escapes	Op	-
3.2	No. of planned operations	Org	-
<i>Boat maneuvering</i>			
4.1	No. of near-misses and escapes	Op	-
<i>Accumulation of dead fish and attraction of predators</i>			
5.1	Time between mort collections	Op/org	-
5.2	No. of near-misses and escapes	Op	-
<i>Dropping of objects</i>			
6.1	No. of near-misses and escapes	Op	-
<i>Training and competence of personnel</i>			
7.1	Fraction of operators with crane certificate	Org	-
7.2	Fraction of operators with boat certificate	Org	-
7.3	Fraction of operators with completed training	Org	Øien and Sklet (2001a)
7.4	Fraction of operators with formal education	Org	Øien and Sklet (2001a)
7.5	Avg. number of years' experience in the fish farming industry	Org	-
7.6	Avg. number of years' experience with specific system	Org	-
<i>Procedures and SJA</i>			
8.1	Fraction of procedures revised last quarter	Org	Øien and Sklet (2001a)
8.2	Number of deviations between procedures and performance	Op/org	Øien and Sklet (2001a)
8.3	Fraction of relevant personnel that performed SJA last year	Org	Øien and Sklet (2001a)
8.4	Fraction of critical operations performed with SJA	Org	-
8.5	Fraction of operators informed of risk analysis last quarter	Org	Øien et al. (2010)
<i>Planning, organization and deviations</i>			
9.1	Lag on follow-up on reported deviations	Org	-
9.2	Fraction of operation manager to total operators	Org	Øien and Sklet (2001a)
9.3	Number of operator-management meetings last quarter	Org	-
9.4	Reported incidents with pressure from management	Org	-
9.5	Reported incidents with under-staffing	Org	-
9.6	Reported incidents with long working hours	Org	-
<i>Inspection, maintenance and control</i>			
10.1	Fraction of critical operations performed with control	Op/org	Øien and Sklet (2001a)
10.2	Backlog maintenance on critical safety equipment	Tech/op/org	Thorsen and Njå (2014)
10.3	Amount of unplanned corr. maintenance on critical equipment	Tech/op/org	Øien and Sklet (2001a)
<i>Design and technical condition</i>			
11.1	Number of repeating failures	Tech	Øien and Sklet (2001a)
11.2	Time left of design life	Tech/org	-
11.3	No. of near-misses and escapes caused by design flaws	Tech/op	-
11.4	No. of temporary solutions and quick fixes	Tech/op	-

## Discussion

Unlike the O&G industry, there are few technical safety barriers to prevent accidents within marine fish farming. The floating collar, net and mooring system are installed to contain fish and secure integrity of the farm, but there are few other technical means for preventing escapes. The mort collection system does reduce the risk of escape by prevent-

ing dead fish from accumulating, but the system also presents a risk of escape through potential interactions with the net. Furthermore, fish farmers do perform recaptures to limit exposure after escapes, but the indicators are primarily a means for preventing the escapes from happening.

The assessment of the Directorate of Fisheries' database indicates that the selected tech/org factors have been direct or indirect causes for previous escapes. However, the database provides no grounds for verifying organizational factors' influence on the risk of escape. Neither does it provide grounds for verifying if a series of near misses are an indication of an upcoming escape. Furthermore, the identified indicators have not gone through any quantitative rating with respect to the indicator requirements described in Section 2.2.2. In general, the lack of technical safety barriers, has made it a challenge to identify appropriate technical indicators.

The indicator 'number of near misses and escapes' is based on the assumption that the number of incidents related to a given operation indicates a risk of escape for that particular activity. For instance, if delousing operations experience frequent incidents, extra attention is required in order to mitigate the problem. The number of near misses may perhaps provide a leading indication of upcoming escapes, thus it may be regarded as a separate indicator. However, this relation is uncertain and needs further assessment.

### **Frequency of measurements**

The frequency of measurements depends upon the different company' own practices and the sea conditions at specific locations. For instance, some fish farmers do not practice towing of fish, and northern fish farms are less prone to sea lice and thus need fewer delousing processes. Consequently, as the thesis does not emphasize a specific location or company, no recommendations for frequency of measurements are given.

### **Implementation of indicators**

Some of the measurements required to implement the proposed indicators may already exist at fish farming companies. Deviations, incidents and failures are examples of aspects that companies are expected to have control over. It does not mean that the indicators already exist, but that the needed data is available. Of importance is that indicator values do not give sufficient information of the risk of escape on their own. A baseline or reference level must be determined and a risk acceptance limit set as to determine when risk-mitigation measures are to be performed.

The total effect on risk of escape should be estimated, and with measurements on several risk-influencing factors, it might be possible to determine exactly where the significant risk is located. It is important that operators are informed of the ongoing measurements and that they are encouraged to report deviations, failures and incidents. Many of the selected indicators may require long-term measurements before a trend is developed. For instance, the fraction of operators with completed training is relatively constant and the indicator must be monitored for a longer period before significant deviations are likely to occur. Again, some sort of reference level is required, i.e. what fraction of operators with completed training is acceptable.

To estimate the total effect on risk, one have to determine the state of each RIF, which is measured by the set of indicators chosen for each factor. Subsequently, the individual RIFs' effect on risk is combined to express the total effect on fish escape. Figure 4.7 illustrates how the state of a risk-influencing factor might change with changing indicator values. Three indicators measure the factor and the red line illustrates the state of the RIF. Increasing indicator-values imply negative deviations from normal conditions, i.e. increased risk of escape. However, this is not necessarily the case. Indicator-values should be substituted to an unambiguous scale where the effect of high and low values are unanimous, i.e. a scale where high values imply positive effect on risk and low values imply negative effect, or vice versa.

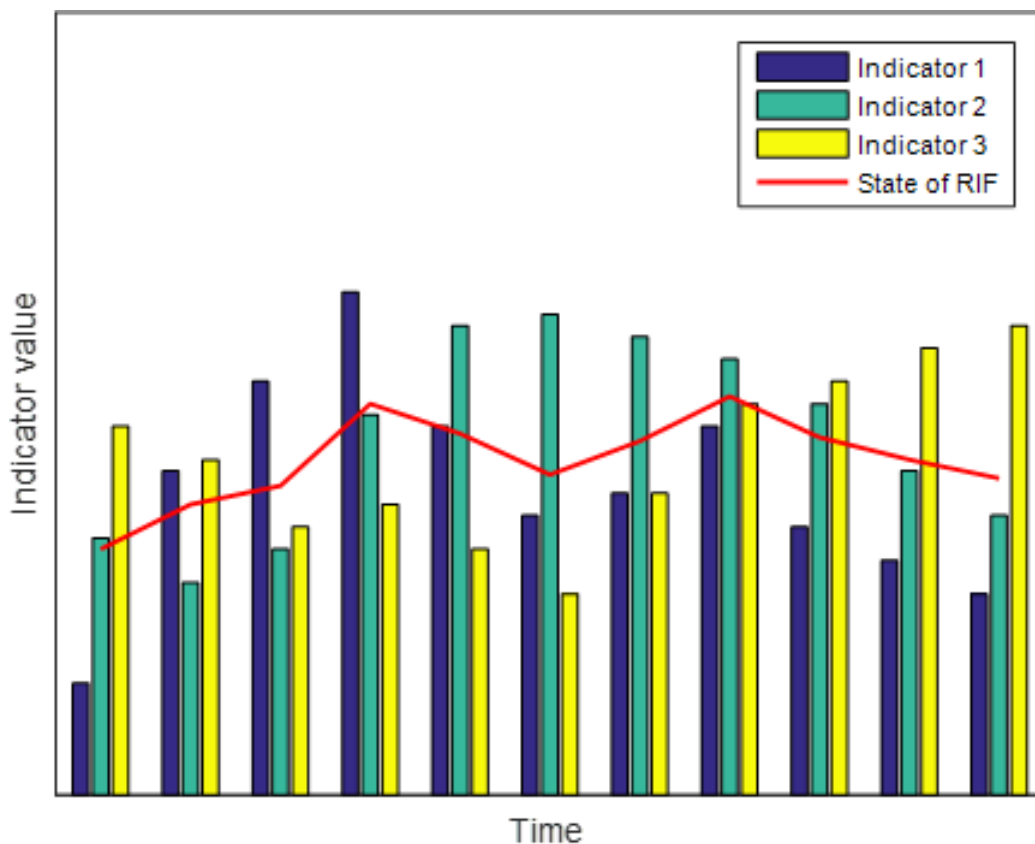


Figure 4.7: Illustration of potential change in indicator value and effect on RIF.

Assume that changes in a certain risk level are covered by changes in three risk-influencing factors, Figure 4.8. The plot illustrates how changes in these three factors may affect the risk. The individual RIFs might not necessarily have equal effect on risk such that an increase in RIF 1 can be more significant than an increase in RIF 3. This also applies for individual indicators measuring a RIF. The blue line illustrates the maximum allowed effect on risk. If the red line exceeds the acceptance limit, risk-mitigation measures are required. Type of mitigation depends on the situation, and by assessing the data, it might be possible to determine which factor/indicator represents the most significant risk. By this approach, the most appropriate mitigation measure can be applied.

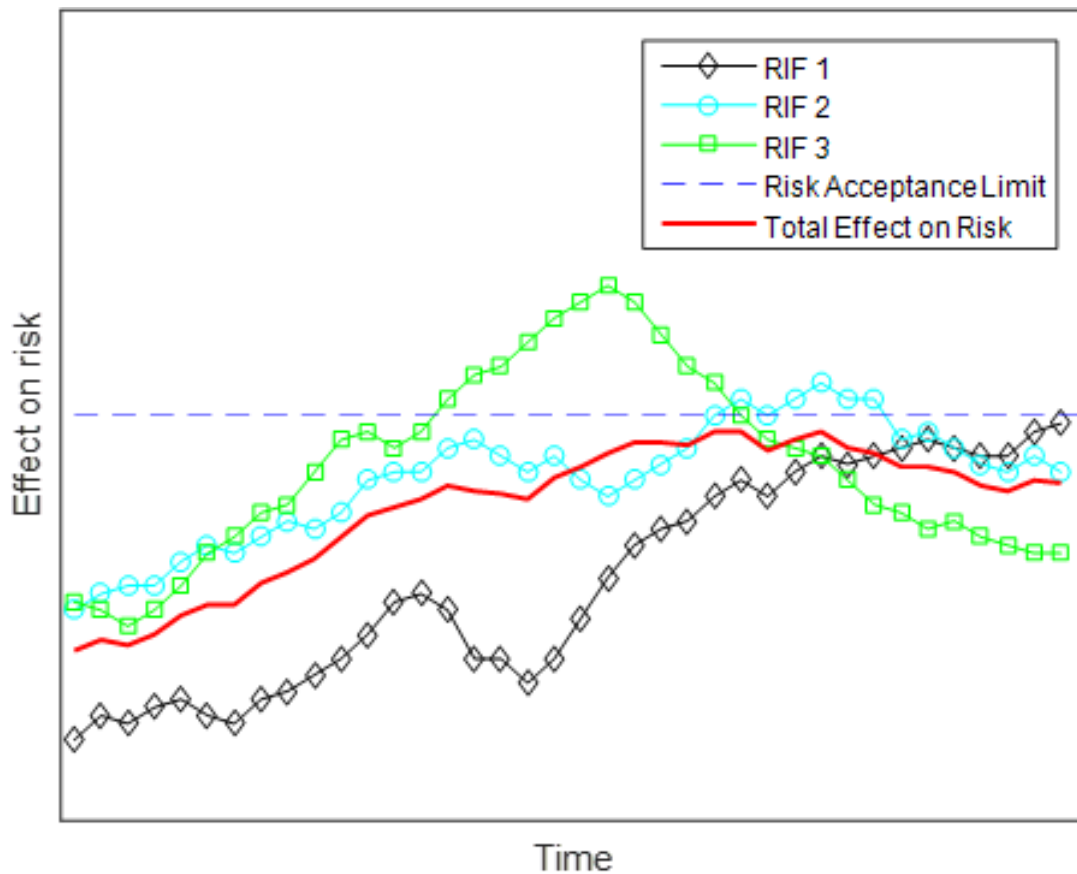


Figure 4.8: Illustration of potential change in RIF and effect on risk.

### Determining the state of RIFs

To illustrate how indicators may be applied to measure the state of RIFs, an example is made of the indicator ‘lag on follow-up of reported deviations’. The example is based on the procedure for quantifying organizational factors effect on risk described by Øien and Sklet (2001a). It aims to demonstrate how changes in measured indicator values indicate a change in the relative risk level by altering the state of its RIF. In reality, there are significant uncertainties regarding the validity of such work. It presumes that indicators sufficiently measure the identified factors, and that the RIFs sufficiently cover the risk of escape. For quantifying the effect of change in technical risk indicators, Øien and Sklet (1999) take basis in technical safety barriers and utilize an existing QRA. However, because of lack of technical safety barriers and less prevalent use of software, it is presumed challenging to adapt this procedure to monitor the risk of escape. However, with available data and expert judgment it may be possible to utilize a similar approach as for organizational indicators.

#### *Application of the indicator ‘lag on follow-up of reported deviations’*

Both indicators and risk-influencing factors are given a rating between 1 and 5, where one is the worst and five the best. The RIFs’ ratings are based on the value(s) of their respective indicator(s). If multiple indicators measure a factor, the indicators may be weighted individually depending on how their relative importance is rated. The factor rating is then the sum of the products of the individual indicator ratings and weightings. However, if only one indicator measures a factor, the indicator’s rating is also the factor’s

rating.

The indicator ratings are linked with actual performance/measurements as shown in Figure 4.9. The appointed values imply that more than ten remaining deviations are not credited, and that less than two reported deviations receive a maximum rating of 5. The values are hypothetical and expert judgment is considered as key input in determining these extremes.

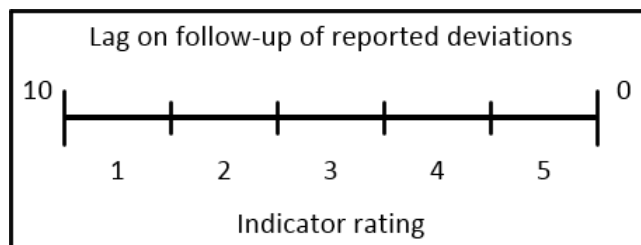


Figure 4.9: Extremes for the indicator ‘lag on follow-up of reported deviations’. Adapted from Øien and Sklet (2001a)

The indicator is assigned to determine the state of the RIF ‘planning, organization and deviations’. Measurements are taken every month and the aim is to quantify how the lag on follow-up of reported deviations develops from month to month. This is again a measure of the relative risk-development from month to month.

Assume that deviations have been recorded during a one-year period. The indicator then develops as shown in Table 4.17. For simplicity, it is assumed that only this indicator measures the factor, thus the factor rating equals the indicator rating. The state of the factor, 1-5, is described as very bad, bad, mediocre, good or very good, respectively.

Table 4.17: Hypothetical reporting of non-compliance reports during a one-year period.

Month	Reported	Total	Handled	Lag	Indicator rating	State of RIF
January	3	3	2	1	5	Very good
February	3	4	2	2	4	Good
March	5	7	4	3	4	Good
April	1	4	2	2	4	Good
May	4	6	1	5	3	Mediocre
June	0	5	2	3	4	Good
July	3	6	2	4	3	Mediocre
August	6	10	2	8	1	Very bad
September	2	10	3	7	2	Bad
October	0	7	2	5	3	Mediocre
November	2	7	0	7	2	Bad
December	1	8	5	3	4	Good

The state of the risk-influencing factor has been determined based on the indicator’s value. It is evident how the factor’s condition changes with time and a similar approach may be used for the remaining factors. The total effect on risk can be estimated by combining results from all risk-influencing factors. However, because the procedure is complex and benefits from the use of software, it is not illustrated in this thesis.



#### 4.3.4 Model with RIFs and indicators

A model is created to illustrate how RIFs and indicators may influence each other. The model is given in Figure 4.10 and is inspired by work by Øien and Sklet (2001a), Nyheim et al. (2012) and Haugen et al. (2012). The arrows indicate the direction of influence and the model is divided into four layers. The organizational factors are underlying aspects, which may influence one or more operational/technical factor. These factors are assumed to have more direct effect on the risk of escape, and are associated with a specific hazard. The hazard is again linked with the escape of fish.

This model considers the specific hazard ‘interactions between net and sinker tube’, but a model involving all hazards could also be created. However, for the purpose of this thesis, it is considered sufficient to illustrate the concept/idea with a smaller example.

The distinction between operational, technical and organization factors/indicators is not always obvious, nor is it regarded as very important. Hence, there may be some discrepancies between how factors have been categorized previously and how they are illustrated in Figure 4.10. However, it is believed that the emphasis should be on sufficiently covering the risk that is to be monitored, and not how factors and indicators are categorized.

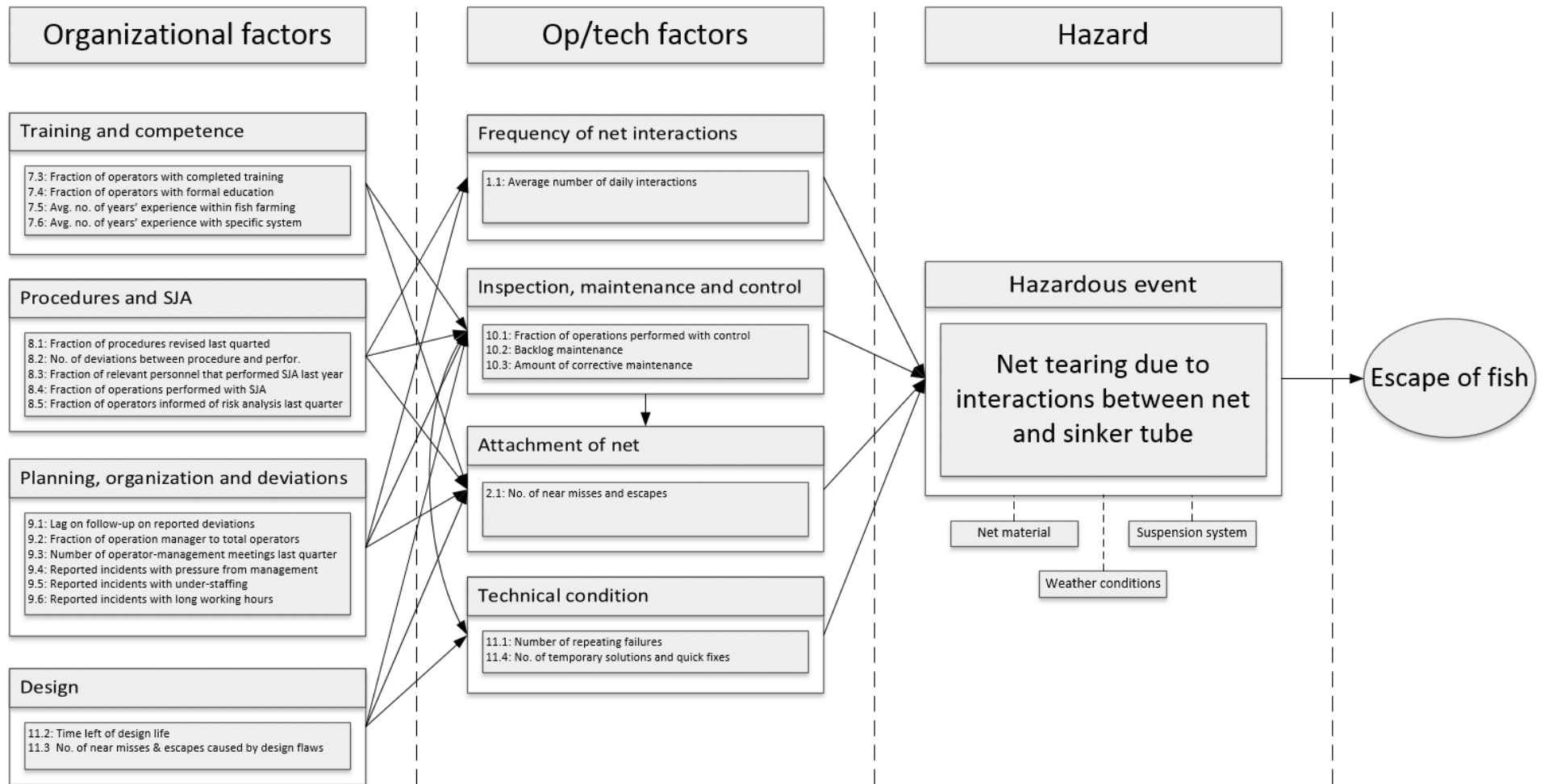


Figure 4.10: Model with RIFs and indicators for the hazard 'net tearing due to interactions between net and sinker tube'.

# Chapter 5

## Conclusion and recommendations for future work

### 5.1 Conclusion

The Directorate of Fisheries' database contains information on what have caused escapes in the past and may be a valuable asset in preventing future escapes. However, as it is prone to certain limitations and challenges, some actions are required before the database is made open access and can be utilized to a greater extent. In this regard, the thesis suggests potential measures to improve the database's usefulness and validity. A complete rework is recommended to ensure that all events are categorized correctly and consistently. This is essential in order for the extracted data to provide a valid representation of the causal picture. It is further recommended to investigate the possibility of implementing organizational aspects with influence on the risk of escape. Such factors may be underlying and initiating aspects leading to the escape of fish.

In analogy with the methods developed in the O&G industry, this thesis provides insights on how the concept of risk indicators may be applied to marine fish farming. A proposed set of risk-influencing factors and indicators are presented as a means for monitoring the risk of escape. They are, however, purely theoretical and have not been tested or approved by the industry. Additionally, the lack of supplementary data has made it a challenge to verify appropriate indicators. Furthermore, the application of relevant software is presumed little prevalent within fish farming. Thus, the quantification of effect on risk may provide an additional challenge. However, it is believed that an approach utilizing expert judgment and relevant data can be applied as well.

The concept of risk indicators is generally considered a viable means in the works of reducing fish escapes from marine fish farms. However, it is not without its challenges and should not act as a sole measure for handling risk. In general, the validity related to application of indicators is uncertain, and there is a lack of proven correlations between indicators and major accidents. This uncertainty is greatest when indicators originate farther into the course of events, i.e. organizational indicators. And because there are few evident technical safety barriers to prevent escapes, the suggested indicator set is mainly governed by such organizational aspects.

## 5.2 Future work

With regard to future work on the subjects covered by this thesis, the following recommendations are given:

- Looking at and learning from previous events is considered a vital part of preventing future escapes. In this regard, the Directorate of Fisheries' database appears as an asset with great potential. Hence, it is recommended to consider the suggestions given in this thesis, and to further investigate the potential use of this database and how it may be exploited to prevent future escapes from marine fish farms.
- It is recommended to further assess the applicability of the concept of risk indicators to marine fish farming. Furthermore, the developed indicators lack testing and expert judgment, and it is advised to put more thought and effort into identifying appropriate indicators.
- It is recommended to investigate for alternative approaches for quantifying the risk of escape. While fish farming companies might not have a QRA with an established risk level as basis, there may be other approaches which can be utilized to express changes in the risk of escape.

# Bibliography

- Aarhus, I. J., Høy, E., Fredheim, A., and Winther, U. (2011). *Kartlegging av ulike teknologiske løsninger for å møte de miljømessige utfordringene i havbruksnæringen*. SINTEF Fiskeri og Havbruk AS, Trondheim.
- Aas, K. and Midling, K. Ø. (2005). *Torsk som rømmer - en atferdsstudie i merd*. Fiskeriforskning.
- Akvagroup (2015a). Akva group - leading supplier of feed barges. Available at <http://www.akvagroup.com/products/cage-farming-aquaculture/feed-barges>. [accessed in April 2016].
- Akvagroup (2015b). Automatic system for collecting morts. Available at <http://www.akvagroup.com/products/cage-farming-aquaculture/mort-collector>. [accessed in January 2016].
- Akvagroup (2015c). Optimum oxygen levels and faster growth. Available at <http://www.akvagroup.com/products/cage-farming-aquaculture/net-cleaning-systems>. [accessed in January 2016].
- Akvakulturdriftsforskriften (2011). *Forskrift om drift av akvakulturanlegg*. Nærings- og fiskeridepartementet, Oslo.
- Andreassen, O. and Robertsen, R. (2014). *Nasjonale ringvirkninger av havbruksnæringen*. Nofima, Tromsø.
- Anon. (2012). *Lakselus og effekter på vill laksefisk - fra individuell respons til bestandseffekter*. Temarapport fra vitenskapelig råd for lakseforvaltning nr. 3, 56 s., Trondheim.
- Aqualine (2015). Fleksible, robuste og slagsterke rør i hardt vær. Available at <http://www.hallingplast.no/referanser/fleksible-robuste-og-slagsterke-roer-i-hardt-vaer/>. [accessed in March 2016].
- Aven, T. (1992). *Reliability and Risk Analysis*. Springer Science & Business Media.
- Aven, T. (2008). *Risk analysis: Assessing Uncertainties Beyond Expected Values and Probabilities*. John Wiley & Sons, Ltd, West Sussex.
- Bjelland, H. V., Høi, E., Rundtop, P., Frank, K., and Sunde, L. M. (2012). *Løsninger og utfordringer for utøvelse av biomassekontroll i lakseoppdrett*. SINTEF Fiskeri og havbruk AS, Trondheim.

- Bjerkestrand, B., Bolstad, T., and Hansen, S. J. (2013). *Akvakultur VG2: Havbruk i Norge*. Forlaget Vett & Viten, Drammen, 2nd edition.
- Botngaard AS (2013). Sikker og effektiv avlusing av oppdrettslaks. Available at [http://www.skattefunn.no/prognett-skattefunn/Artikkel/Sikker\\_og\\_effektiv\\_avlusing\\_av\\_oppdrettslaks/1253987881789?lang=no](http://www.skattefunn.no/prognett-skattefunn/Artikkel/Sikker_og_effektiv_avlusing_av_oppdrettslaks/1253987881789?lang=no), note = [accessed in March 2016].
- Deady, S., Varian, S. J., and Fives, J. M. (1995). The use of cleaner-fish to control sea lice on two irish salmon (*salmo salar*) farms with particular reference to wrasse behaviour in salmon cages. *Aquaculture*, 131:73–90.
- DELWP (n. d.). Department of environment, land, water & planning. Available at [http://www.depi.vic.gov.au/\\_data/assets/image/0017/210482/aquaculture-cage-2.jpg](http://www.depi.vic.gov.au/_data/assets/image/0017/210482/aquaculture-cage-2.jpg). [accessed in January 2016].
- Directorate of Fisheries (2015a). Erfaringsbase - rømming i forbindelse med matfiskproduksjon. Available at <http://www.fiskeridir.no/Akvakultur/Drift-og-tilsyn/Roemming/Erfaringsbase/Matfiskproduksjon>. [accessed in March 2016].
- Directorate of Fisheries (2015b). Erfaringsbase - rømming i forbindelse med matfiskproduksjon: Dødfiskoppsamler.
- Directorate of Fisheries (2015c). Erfaringsbase - rømming i forbindelse med matfiskproduksjon: Notskift med treing.
- Directorate of Fisheries (2015d). Erfaringsbase - rømming i forbindelse med matfiskproduksjon: Pm2.1 arbeidsoperasjoner.
- Directorate of Fisheries (2015e). Erfaringsbase - rømming i forbindelse med matfiskproduksjon: Pm2.4 sleping av merder.
- Directorate of Fisheries (2016a). Biomassestatistikk: Innrapportert beholdning av fisk ved månedslutt.
- Directorate of Fisheries (2016b). Biomassestatistikk: Innrapporterte antall merder og lokaliteter i bruk.
- Directorate of Fisheries (2016c). Rømming. Available at <http://www.fiskeridir.no/Akvakultur/Registre-og-skjema/Skjema-akvakultur/Roemming>. [accessed in April 2016].
- Directorate of Fisheries (n.d.). Akvakultur - godkjente lokaliteter: Lokaliteter i sjø. Available at <http://kart.fiskeridir.no/default.aspx?gui=1&lang=2>. [accessed in March 2016].
- Fenstad, J., Osmundsen, T., and Strkensen, K. V. (2009). *Fare på merde? Behov for endret sikkerhetsarbeid ved norske oppdrettsanlegg*. NTNU Samfunnsforskning AS, Trondheim.
- Fleming, I. A., Hindar, K., Mjølnerød, I. N., Jonsson, B., Balstad, T., and Lamberg, A. (2000). Lifetime success and interactions of farm salmon invading a native population. *Biological Sciences*, 267:1517–1523.

- Føre, H. M. and Lien, A. M. (2014). *Utredning og tiltak mot skader på not ved vasking i sjø*. SINTEF Fiskeri og havbruk AS, Trondheim.
- Haugen, S., Seljelid, J., Nyheim, O. M., and Sklet, S. (2012). *Major accident risk indicators, Part I: A generic method for identification*. NTNU, Trondheim.
- Heuch, P. A., Gettinby, G., and Revie, C. W. (2011). Counting sea lice on atlantic salmon farms - empirical and theoretical observations. *Aquaculture*, 320:149–153.
- Hindar, K., Flemin, I. A., McGinnity, P., and Diserud, O. (2006). Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES Journal of Marine Science*, 63:1234–1247.
- Høiseth, M., Heide, M., Høi, E., and Sunde, L. M. (2009). *Rømming tilknyttet transport av levende fisk i oppdrettsnæringen*. SINTEF Fiskeri og havbruk AS, Trondheim.
- Holmen, I. M. and Thorvaldsen, T. (2015). *Godt sikkerhetsarbeid - eksempler fra ulike næringer*. SINTEF Fiskeri og havbruk AS, Trondheim.
- HSE and CIA (2006). *Developing process safety indicators: A step-by-step guide for chemical and major hazard industries*. Health and Safety Executive.
- IEC (2013). Electropedia: Risk assessment/ safety and risk reduction. Available at <http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=903-01-07>. [accessed in April 2016].
- IK-Akvakultur (2005). *Forskrift om internkontroll for å oppfylle akvakulturlovgivningen*. Nærings- og fiskeridepartementet, Oslo.
- Institute for Work & Health (2011). *Benchmarking organizational leading indicators for the prevention and management of injuries and illnesses*. Institute for Work & Health, Toronto.
- Jensen, Ø. (2006). *Gjennomgang av tekniske krav til oppdrettsanlegg - basert på rømmingstilfeller i januar 2006*. SINTEF Fiskeri og havbruk AS.
- Jensen, Ø., Dempster, T., Thorstad, E. B., Uglem, I., and Fredheim, A. (2010). Escapes of fishes from norwegian sea-cage aquaculture: causes, consequences and prevention. *Aquaculture Environment Interactions*, 1:71–83.
- Laksefakta (2015). Fra rogn til mat. Available at <http://www.laksefakta.no/Norsk-havbruk/Laksens-livssyklus/Les-mer-om/Fra-rogn-til-mat>. [accessed in February 2016].
- Laketildelingsforskriften (2005). *Forskrift om tillatelse til akvakultur for laks, ørret og regnbueørret*. Nærings- og fiskeridepartementet, Oslo.
- Luseprosjektet (2012). *Badebehandling med hydrogenperoksid i brønnbåt*. Lusedata.
- Luseprosjektet (2013). *Badebehandling med Alpha Max, Betamax og Salmosan i merd*. Lusedata.

- Marine Harvest (2015). Salmon farming industry handbook 2015. Document from webpage: <http://www.marineharvest.com/globalassets/investors/handbook/2015-salmon-industry-handbook.pdf>. [accessed in February 2016].
- Markeset, T. (2013). Operation and maintenance management [powerpoint slides]. Lecture in TEK-3001 Operation and maintenance management at UiT - The Arctic University of Norway.
- Ministry of Fisheries and Coastal Affairs (2009). *Strategy for an Environmentally Sustainable Norwegian Aquaculture Industry*. Norwegian Ministry of Fisheries and Coastal Affairs, Oslo.
- Ministry of Trade, Industry and Fisheries (2013). Escaped fish. Available at <https://www.regjeringen.no/en/topics/food-fisheries-and-agriculture/fishing-and-aquaculture/farmed-salmon/escaped-fish/id730685/>. [accessed in February 2016].
- Naylor, R., Hindar, K., Fleming, I. A., Goldberg, R., Williams, S., Volpe, J., Whoriskey, F., Eagle, J., Kelse, D., and Mangel, M. (2005). Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. *BioScience*, 5:427–437.
- NEA (n.d.). Sea lice. Available at <http://www.miljodirektoratet.no/en/Areas-of-activity1/Species-and-ecosystems/Salmon-trout-and-Arctic-char/Pressures-on-salmonids/Sea-lice/>. [accessed in February 2016].
- Ni, S., Zhuang, Y., Gu, J., and Huo, Y. (2016). A formal model and risk assessment method for security-critical real-time embedded systems. *Computers & Security*, 58:199–215.
- Nilsen, A., Viljugrein, H., Røsæg, M. V., and Colquhoun, D. (2014). *Rensefiskhelse - kartlegging av dødelighet og dødelighetsårsaker*. Veterinærinstituttet, Oslo.
- Norwegian Standard (2009). *NS 9415 Floating fish farming installations - design, dimensioning, construction, installation and operational requirements*. Standard Online AS, Oslo.
- NRK (2005). Nr.no: Dette er sabotasje. Available at [http://www.nrk.no/nyheter/distrikt/nrk\\_troms\\_og\\_finmark/finmark/4796939.html](http://www.nrk.no/nyheter/distrikt/nrk_troms_og_finmark/finmark/4796939.html). [accessed in April 2016].
- Nyheim, O. M., Haugen, S., Seljelid, J., and Sklet, S. (2012). *Major accident risk indicators, Part II: Case study*. Safetec Nordic AS, Trondheim.
- NYTEK (2012). Forskrift om krav til teknisk standard for flytende akvakulturanlegg.
- Øien, K. (2001). Risk indicators as a tool for risk control. *Reliability Engineering & System Safety*, 74:129–145.
- Øien, K., Massaiub, S., Tinmannsvika, R. K., and Strsetha, F. (2010). *Development of Early Warning Indicators based on Resilience Engineering*. Paper presented at PSAM 10, Seattle.



- Øien, K. and Sklet, S. (1999). *Metode for å utarbeide tekniske risikoindikatorer*. SINTEF Teknologiledelse, Trondheim.
- Øien, K. and Sklet, S. (2001a). *Metodikk for utarbeidelse av organisatoriske risikoindikatorer*. SINTEF Teknologiledelse, Trondheim.
- Øien, K. and Sklet, S. (2001b). *Risk Analyses during Operation (The Indicator Project) Executive Summary*. SINTEF Industrial Management, Trondheim.
- Øien, K., Utne, I. B., and Herrera, I. A. (2011). Building safety indicators: Part 1 - theoretical foundation. *Safety Science*, 49:148–161.
- Økokrim (2008). *Rømt oppdrettsfisk*. Økokrim, Oslo.
- Rajasekar, S., Philominathan, P., and Chinnathambi, V. (2013). *Research methodology*. Bharathidasan University, Tiruchirapalli.
- Rambøll (2010). *Risikomodell Havbruk: Forhold som påvirker personsikkerhet og risiko for rømming av fisk*. Rambøll, Trondheim.
- Skiftesvik, A. B., Bjelland, R. M., Durif, C. M. F., Johansen, I. S., and Browman, H. I. (2013). Delousing of atlantic salmon (*salmo salar*) by cultured vs. wild ballan wrasse (*labrus bergylta*). *Aquaculture*, 402-403:113–118.
- SNL (2014). Fiskeri og kystdepartementet. Available at [https://snl.no/Fiskeri-\\_og\\_kystdepartementet](https://snl.no/Fiskeri-_og_kystdepartementet). [accessed in February 2016].
- SNL (2015). Norges geografi. Available at [https://snl.no/Norges\\_geografi](https://snl.no/Norges_geografi). [accessed in March 2016].
- SSB (2015). Akvakultur, 2014, endelige tall. Available at <http://ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett/aar/2015-10-29#content>. [accessed in April 2016].
- Stien, L. H., Dempster, T., Bui, S., Glaropoulos, A., Fossedeigen, J. E., Wright, D. W., and Oppedal, F. (2016). ‘snorkel’ sea lice barrier technology reduces sea lice loads on harvest-sized atlantic salmon with minimal welfare impacts. *Aquaculture*, 458:29–38.
- Størkersen, K. V. (2012). Fish first: Sharp end decision-making at norwegian fish farms. *Safety Science*, 50:2028–2034.
- Sunde, L. M. (2014). *TEKMAR 2012 - Innovasjon i havbruk*. SINTEF Fiskeri og havbruk AS, Trondheim.
- Thorsen, H. K. and Njå, O. (2014). *Monitoring major accident risk in offshore oil and gas activities by leading indicators*. Paper presented at PSAM 12, Honolulu.
- Thorvaldsen, T., Holmen, I. M., and Moe, H. K. (2013). *Menneskelige faktorer og rømming fra lakseoppdrettsanlegg*. SINTEF Fiskeri og havbruk AS, Trondheim.
- Thorvaldsen, T., Holmen, I. M., and Moe, H. K. (2015). The escape of fish from norwegian fish farms: Causes, risks and the influence of organizational aspects. *Marine Policy*, 55:33–38.

- Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O. T., Nilsen, F., Horsberg, T. E., and Jackson, D. (2013). Salmon lice - impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases*, 36:171–194.
- USCG (2001). *Risk-Based Decision Making Guidelines: Volume 3 - Procedures for Assessing Risk*. United States Coast Guard (USCG), Washington, D.C.
- Zolotukhin, A. (2014). Oil and gas resources and reserves - with emphasis on the arctic [powerpoint slides]. Lecture in AT-327 Arctic Offshore Technology at UNIS - the University Center in Svalbard.