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Fish Escape and Models to Assess Influential Factors

Master's thesis in Marine Technology
Supervisor: Ingrid Bouwer Utne
June 2019

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Abstract

This thesis examines the issues in aquaculture with a particular focus on fish escape and safety management. The context this thesis is built upon is a comprehensive literature study upon matters of relevance in aquaculture and two databases containing historical information about how previous fish escapes have occurred. The first database was created from numerous reports issued to the Directorate of Fisheries by fish farming companies, containing information of events with escapes and suspected escapes in 2016. The latter database was created by the Directorate of Fisheries and contains information on fish escape events from 2010 to 2016.

The databases provide insight into different configurations and causes of fish escape with associated operations, equipment, and components. The categorised findings from the database have been subject to statistical analyses to estimate the extent of fish escape connected to different configurations of fish escape.

To present sufficient information about different configurations of fish escape, the paper assesses the structure of an aquaculture farm, a variety of marine operations and the safety management systems. The findings perceive fish escape as a result of poor management of the fish farming system.

The information from the database and literature studies have been used to create a holistic designed Bayesian Belief Network by use of GeNie, addressing influential factors in an operative context. Additional networks were created to review the organisational influence on safe operations. The networks have a dual function. It can be utilised purely graphical to understand how fish escape occurs, or it can be converted to a quantitative network to determine influence from various factors. The incentive for developing such models is to create a medium where organisational changes and work practices can be measured.

The thesis concludes that the model can be used as a supportive tool in risk management, preferably combined with the Operational Safety Condition method. The strength of the model lies within addressing corresponding relationships between man, technology and organisation which allows for easy identification of risk influential factors.

Sammendrag

Denne avhandlingen undersøker problemer relatert til fiskerømming og sikkerhetsstyring i havbruk. Grunnlaget denne avhandlingen bygger på er en litteraturstudie av akvakultur og to databaser som inneholder historisk informasjon om hvordan fiskerømming har tidligere skjedd. Rapporter om rømming og mistanke om rømming Fiskeridirektoratet mottok i løpet av 2016 er grunnlaget for den første databasen. Den andre databasen ble opprettet av Fiskeridirektoratet og inneholder informasjon om fiskerømminger i tidsrommet fra 2010 til 2016.

Databasene gir innsikt i ulike årsaker til fiskeflukt, og hvordan disse har oppstått. Den gir innsikt i hvilken sammenheng rømmingen skjedde i, med tilhørende utstyr og komponenter. De kategoriserte funnene fra databasen ble brukt i statistiske analyser for å anslå omfanget av fiskerømming som følge av de forskjellige hendelsene.

For å få frem tilstrekkelig informasjon om forskjellige måter fisk kan rømme på, går avhandlingen gjennom strukturen til et oppdrettsanlegg, en rekke marine operasjoner og sikkerhetsstyringssystemer. Funnene tilsier at fiskerømming skjer gjerne som en konsekvens av dårlig praksis og kontroll av det fysiske oppdrettssystemet.

Informasjonen fra databasen og litteraturstudiene har blitt brukt til å lage en Bayesiansk nettverk ved bruk av programmet GeNie. Nettverket tar for seg forskjellige faktorer som bidrar til fiskerømming i en operativ sammenheng. Ytterligere nettverk ble lagd for å undersøke den organisatoriske innflytelsen selve selskapet kan ha på fiskerømming. Nettverkene kan anvendes på forskjellige måter. Det kan brukes rent illustrativt for å forstå hvordan fisken rømmer, eller det kan konverteres til et kvantitativt nettverk for å gjennomgå de faktiske forhold. Motivasjonen for å utvikle modellene er for å lage en plattform hvor arbeidspraksis og organisatoriske endringer og kan undersøkes.

Det kan konkluderes med at modellen kan brukes som et nyttig verktøy i risikostyring, gjerne kombinert med informasjon innhentet fra Operation Safety Condition metoden. Fordelen med modellen er at den kan enkelt få frem forholdet mellom menneske, teknologi og organisasjon i sikkerhetsstyring og rømmingshendelser.

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1 Introduction

Since the 1970s there has been observed a rapid rise of the aquaculture industry in Norway. Norway has fortified its position in the international market as the world leading supplier of Atlantic Salmon. The future estimations for value generation from the aquaculture section and repercussions predict a possible yield of 550 billion NOK within 2050, indicating a vast potential for growth (Olafsen et al. (2012)). Followingly, it has sparked vast engagement among researchers, enterprises and the government to fortify the growing industry that will create value for the Norwegian population for years to come. This current era marks the transformation from an experience based to a knowledge-based industry.

Yet, there is a continuous need for improvement, especially in the area of safety management in aquaculture. The production of biomass is accomplished in harsh, unforgiving conditions along the Norwegian coast. These conditions pose a challenge upon the structural and operational context within fish farming. If Norway intends to maintain its lead position in the global seafood industry while reducing the impact upon the environment, it is essential to review the current challenges and propose areas of improvement.

The Norwegian aquaculture is currently a reputation sensitive industry, reasonably through its negative impact upon the ecological environment. Besides releasing organic waste in the form of excess feed and fish excrement which pollutes the local seabed, fish escape affects the population of wild salmon. Escaped fish induces ecological pollution that purges the wild population through interbreeding, territorial competition and transferring of pathogens and parasites. The effect upon the environment has resulted in the degradation of the wild Atlantic salmon stock in addition to diverse marine species. The industry has a responsibility towards nature to reduce the ecological impact to ensure the biodiversity of species and preserve the public perception of fish farming. The latter is important to justify political acceptance for further expansion of the industry.

Fish escape is designated as the most serious accident in the industry that might occur during all phases of production. Preventive means regarding reduction in occurrence and quantity of fish escape have been implemented in the last decade through statutory requirements, with significant results. The statutory standards that were introduced apply for the technical aspect at a facility, which implies that the organisational and human aspect has a large influence upon escape accidents in the last decade. This perceives fish escape as a result of incorrect handling and management of the physical system. Consequently, this highlights the need for enhancing the safety management system, especially as inadequate risk assessments are revealed to be a contributing factor (Thorvaldsen et al. (2015)).

The Norwegian Directorate of Fisheries possesses a database based on data acquisition and reports from the aquaculture industry regarding fish escape. Categorised historical data upon this matter provides useful information and statistical values which can be applied to the context of risk analysis. The approach of using historical data is common in managing and enhancing safety within organisations (Holen et al. (2017)). This enables a deductive approach in order to understand the characteristics of accidents that occur in different operational contexts. These characteristics must be comprehended to ensure safe and sustainable cultivation of Atlantic salmon along the Norwegian coast.

1.1 Research Objectives

The objective is to investigate historical data of fish escape to address and acquire a deeper knowledge of issues that compromises the integrity of aquaculture systems. Furthermore, the safety management system in aquaculture is evaluated by conducting a literature study to identify areas of improvement. Bayesian Belief Networks is utilised to review how these issues can be managed.

1.2 Scope & Limitations

This thesis is narrowed down to comprehend the risk of escape during the growing phase in seawater, excluding land-based and offshore facilities. In addition, the paper solely focuses on open, conventional gravity cages that are commercially used.

The acquired data of fish escape has limitations of its own, where certain reports are unfulfilled or inconsistent. To achieve fidelity of the historical data some corrective measures are taken to provide a consistent data set. Further limitations are addressed throughout in this thesis.

2 Background

This chapter presents information about the aquaculture industry and their current practices, safety management system, and challenges.

2.1 The Norwegian Aquaculture Industry

The very start of the Atlantic salmons' life cycle starts on-shore, where fertilised eggs are incubated in commercial hatcheries. When spawned, the fish is kept in tanks on-shore whilst they grow of sufficient size. Once the smoltification transition is finished and the desired size is reached, the smolt is transferred to marine fish farms where the grow-out phase starts. The growing phase in sea water is highly dependent on light, temperature and feed conversion ratio but also constrained by factors such as disease, lice, and fish welfare. Usually, the growing phase lasts for 14-24 months. Once the fish reaches market weight, it is optionally transported by well-boats to an onshore processing facility, or directly processed on-board a slaughtering vessel. After the end of a production cycle, the marine fish farm must fallow for 2 to 6 months before a new generation may be bred for environmental purposes. (Marine Harvest (2018))

The cultivating of salmonids is operation intensive process, whereas certain operations are necessary to be performed daily such as feeding, inspection and retrieving dead fish. Further operations such as cleaning of biofoul, delousing and de-icing are performed periodically. Harvesting and transportation of fish are performed at the end of each generation (Jin et al. (2018)). In common for several operations is the use of vessels that physically interacts with the farm. Among these are well-boats for transportation, bulk carriers for feed supply and dedicated service vessels. (Kristiansen et al. (2017)). Advanced operations such as the strengthening of the mooring system and delousing require specialised vessels (Holmen and Thorvaldsen (2018)). Overall, the industry is prone to frequent stimulus from the environment and personnel which implies that the system is subject to a lot of physical interactions.

2.2 Fish Farming Systems

This section presents the design of the current fish farm system within the defined thesis scope. The purpose is to introduce the reader to the structural context of farming systems. The design of the fish cages depends on the environmental conditions measured on the locality, where the system has to be dimensioned accordingly. The design this thesis investigates is an inshore conventional gravity cage with high-density polyethylene collars providing buoyancy, assisted by hanging weights to maintain the net shape. A large commercial marine fish farm may consist of six or more cages aggregated into one elongated module, depending on the locality and number of production licenses. Each respective cage may contain up to 200 000 units of fish distributed over a large volume (Kristiansen et al. (2017)). Furthermore, to ensure fish welfare there is a limit for the stock density of 25 kg/m^3.

2.2.1 HDPE Pipes

The system is provided buoyancy from high-density polyethylene (HPDE) collars. The dimension of the pipes is determined by the size of the farm and the measured conditions. The characteristics of different HPDE materials differ, but the commonly used types are PE80 and PE100 (Jin et al. (2018)). The number expresses the pressure limit in N/mm over a lifespan of 50 years. This indicates pipes made from PE100 will withstand higher pressure than PE80, even with the same dimensions. Important characteristics for HDPE pipes are flexibility and strength as it is deployed in a dynamic environment and must be able to absorb the motions. Furthermore, the diameter of the pipes determines the buoyancy of the collar. High exposure will require more buoyancy, as drag forces will deform the net more easily. Thus, heavier weights must be attached to maintain the net shape and volume.

2.2.1.1 Sinker and Sinker Tubes

The net needs to maintain its volume while exposed to current, which is done by weights. Depending on the cage profile, two methods are usually used to weight down the net:

by using several sinkers or a single sinker tube. The latter usually applies to conically shaped nets. Conic nets have the advantage of making retrieval of deceased fish easier. Furthermore, the weights are fixed to the floating collar, either mounted to the outer collar itself or the brackets. Brackets are a device that connects the floating pipe to the cage collar. The length of the rope with weights attached must be sufficiently long to avoid any interactions with the net, i.e. the same length as net depth or longer. Precautions regarding abrasion between the net and weights can be done by introducing longer ropes, or by covering the weights with an additional protective layer. (Jin et al. (2018)).

2.2.2 Netting

The net can be made from a range of synthetic fibres and is perhaps the most valuable element on a fish farm. Important characteristics of the material are size, thickness, and shape. The net must be durable and resistant to abrasion and predators. Furthermore, the twine number indicates the density of the net twines which determines the strength of the twines. Mesh size indicates the distance between the knots, which have to be dimensioned appropriately to avoid excessive drag forces from the current. NS 9415 provides guidelines on the technical requirements of cage nets.

In addition to the net, a range of different ropes are used to support the framework of the system. Vertical ropes are attached to the net and floating collar and hold the entire net weight. Waterline ropes circumference the pen at collar level and contain either rope loops or metal bindings which attaches the net to the collar. Rope loops are usually protected by a rubber hose to avoid wear and tear. Furthermore, each crossing of rope is reinforced with additional stitching.

2.2.3 Grid and Mooring System

The mooring system used to stabilise and fortify HPDE modules is a squared grid system assisted by an array of transverse and longitudinal lines anchored at the sea bottom. By connecting several cages into a module, it provides a dynamic system designed to dampen the translations induced by hydrodynamic forces. The grid system is connected to connector plates several metres below the surface to create accessibility to the fish farm for seagoing vessels (Cardia and Lovatelli (2015)). Figure 2.1 displays an example of how the mooring and grid system might be composed.

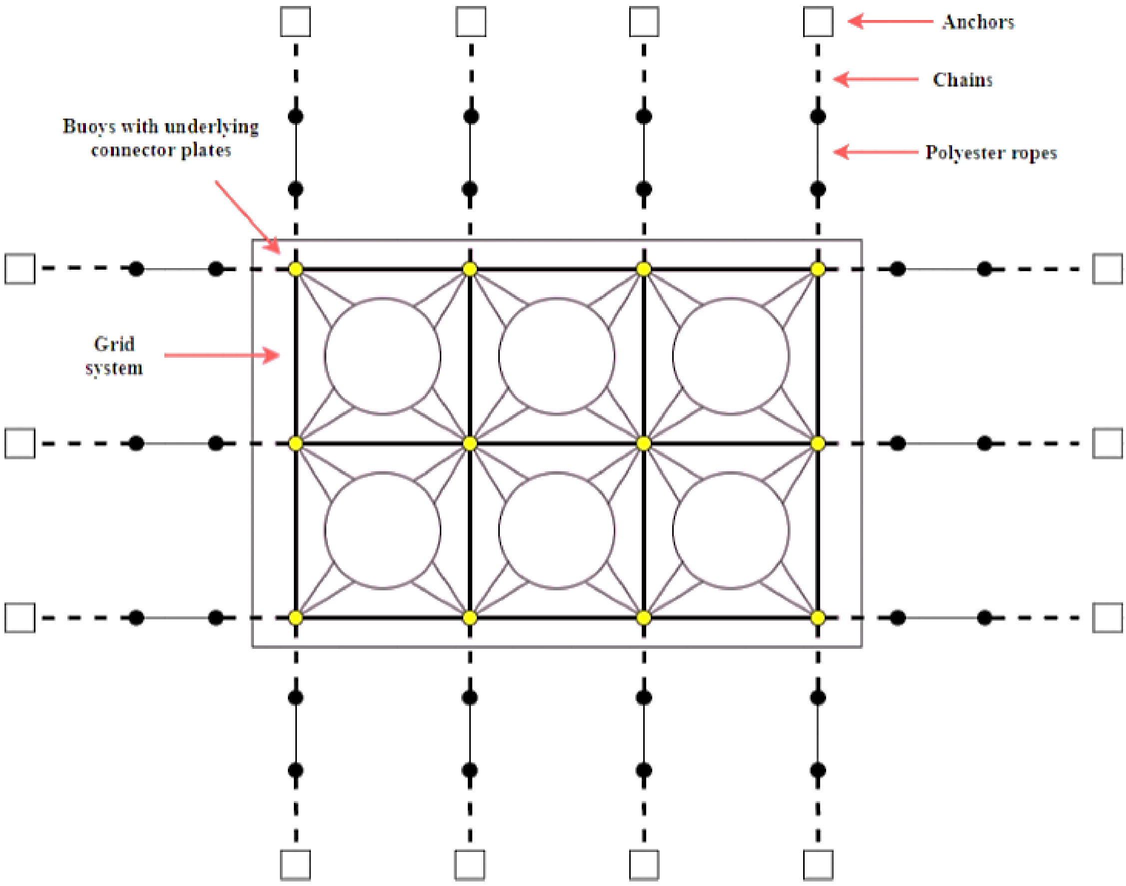

Figure 2.1: Mooring and grid system layout

The mooring and grid system is composed of different components and materials with unique properties. The mooring system consists of polyester ropes, galvanised chains, shackles, buoys, and anchors. The grid system consists of the frame ropes, connector plates, buoys, shackles, and bridles. NS 9415 requires each component used in the system to be accredited by an authorised third party company issued by Norwegian Accreditation.

The mooring lines have both geometrical and elastic properties, achieved through the use of polyester ropes and chains. Polyester ropes are cheap, light and elastic as opposed to the heavy and inductile chains. Chains ensure stiffness through restoring forces induced when the system is dislocated. According to NS 9415, fish farms require a mooring system that can maintain its position given the environmental conditions. The relationship between numbers of cages and mooring lines indicate the level of steadiness of the system. However, excessive stiffness of the mooring and grid system can increase material fatigue and make it prone to snap loads.

2.2.4 Structural Details

Additional reinforcing of the fish farm system can be added prior to the production phase to avoid loss of integrity and followingly fish escape. Impregnated nets may be used to reduce the growth of biofoul and followingly frequency and impact of net cleaning. Furthermore, by combining different types of ropes with different characteristics in the netting, reinforced netting can be installed at the centre of the cage base. This might be advantageous if companies use dead fish collectors which rests on the bottom of the cage. An additional net panel can be sewn into the base net to further reduce the risk of fish escape.

2.3 Selected Operations

This section aims to introduce the reader to selected activities conducted at aquaculture facilities. Potential hazards associated with respective operations are presented and discussed. The following sections were presented in the specialisation project but are re-presented with additional input as it is of relevance.

2.3.1 Upstream transportation of fish

Prior to the growth phase in the sea, the juveniles are transported from the on-shore hatchery to a farm jetty where the fish undergoes a smoltification process. The quality of the juvenile set in seawater is an important factor for further survivability and an excellent end product. This enhances the importance of manipulating the environmental conditions in the early juvenile stages (Føre et al. (2017)). The quality is controlled manually at the hatchery, where the fish is sampled and quantified. This process ensures that the fish is of appropriate size and records the total number of outputs. (Cardia and Lovatelli (2015)).

When the smolt reaches the desired size, the batch is transported by well boats in insulated fish transport tanks equipped with a circulation system to ensure beneficial conditions whilst the system slowly acclimatises the fish to the new water conditions at the site. Transportation of fish is strictly controlled by Regulation for Transportation of Marine Species (FOR-2008-06-17-820), which sets demands within fish handling, disease control and discharging of wastewater. The fish is usually deposited in the pens by pipelines and fish pumps, which requires physical interaction between the fish pen and well boat. Fracture of pipelines or mishandling may cause loss of fish during loading and unloading. (Cardia and Lovatelli (2015)).

2.3.2 Harvesting and downstream transportation of fish

When the salmon reaches the market weight, the production cycle is in the finalising phase. The fish must be harvested, whereas the chosen method depends on the design of the cage, environmental conditions, quantity and density of fish. It is of importance to choose the correct method to harvest the appropriate amount of fish whilst treating it gently. Fish is a fragile product that can easily be damaged or stressed, resulting in lower quality. Harvesting less or more of the planned quantity is undesirable, as continuous sweeps for fish or release of excess fish is a process that discomforts the fish. Thus, harvesting is a process that requires competent operators and divers. Prior to the load phase, the fish has to be brought to the surface and crowded to ease the offload operation.

The purse seine technique is frequently used prior to harvesting large amounts of fish or entirely empty the pen. This technique involves a massive net able to encircle a school of fish. The purse seine consists of a floating line and sinker line in which the latter has pursing rings attached, extending up to the personnel at the surface. Upon pull, the purse encloses the school of fish. Once the divers have made an estimation of the quantity of fish, the purse may be hauled to decrease the volume of the net. The net is then fastened by the handrail, and fish may be transported over to the vessel. (Cardia and Lovatelli (2015)).

Another approach for piling up the fish is by use of lift net, which is initially laid down upon the bottom of the cage. Hooks are located at the perimeter of the net, which allows divers to gradually re-position the hooks closer to the surface as they spiral around the cage. After numerous rounds, the lift net approaches the surface with denser amounts of fish.

Followingly, the personnel at the surface may harvest the fish using the desired method. (Cardia and Lovatelli (2015)). It is worth to notice that if the operation is miscarried, excessive load upon one simple hook might result in a fracture of the net. Crowding of fish is frequently conducted in other operations as well and is usually considered a safe operation. However, issues may occur if the weight attached to the deposited net is entangled in the stationary net and lifted by force.

The fish may be brought on-board well boats by use of pipelines with either vacuum or negative pressure in the storage tanks. The pipelines are placed in the pen, which the fish travels through. To ensure proper conditions during the transportation, oxygen inlets and carbon-dioxide outlets are installed. By using Refrigerated Sea Water (RSW), the cooling process allows for the properties of the fresh fish to be preserved until processing onshore. After transportation of a batch, the entire system of tank and tubes are disinfected to eradicate potential diseases (Ellefsen (2014)). Alternatively, the fish may be transported from the pen to the vessel by scoop nets manoeuvred by cranes. Those nets have a quick release system that may be triggered to easily deposit the fish into containers. (Cardia and Lovatelli (2015)).

2.3.3 Cleaning of biofouling

The frequency of net cleaning differs from different localities given the strategy and conditions found. The use of cleaner fish for lice is strongly connected to the frequency of cleaning. Companies which do use cleaner fish are required to clean the net frequently as the fish might prefer to feed on biofoul over lice. Companies who do not utilise cleaner fish are not forced to clean the net as frequent but have to delouse far more often.

Certain companies choose to use newly impregnated nets when the first generation is deployed in August - October. Impregnated nets may remain in seawater until March or April without necessary flushing. The flushing decreases the efficiency of the impregnation, and thereafter the net is flushed every third week. During the summer the net is usually replaced with a new impregnated net that stays untouched until September, where the process starts again. The temperature regulates the required frequency for net cleaning. With this method, the net is subject to flushing 8 to 10 times during a generation.

(Langøylaks AS (2019))

Clogged nets reduce the water exchange, affecting the fish welfare by decreasing accessible oxygen for the fish. In addition, biofouling facilities the growth of bacteria and parasites. Biofouling adds excess weight to the system and changes the characteristics of the twines, making it more exposed to wear and tear.

Regarding the cleansing methods, commonly used are high-pressure water jets. The water jet is empowered from vessels and is operated by divers. There are however other more sophisticated approaches, such as Remotely Operated Net Cleaners (RONC), a device with rotating disks that are lowered from a service vessel. RONC relies on the power supply from the vessel and thrusters to navigate, assisted by computer operators (Cardia and Lovatelli (2015)).

The use of RONCs might introduce potential complications, as harsh weather conditions and loss of power may disrupt safe operation and retrieval of RONC, leaving it tangled in the net or sunk to the bottom. Such accident might induce holes, initially by excessive loads upon the net or twine fracture during the retrieval process. In addition, sharp blades and excessive pressure from RONC and the jet washer may contribute to holes directly or a partial fracture. Partial fracture gradually weakens the twines, which in first turn leaves unnoticed damages that might develop into holes (Hatlem and Kvamme (2016)).

2.3.4 Lice counting and delousing

Allocating thousands of salmonids in a restricted area allows salmon lice to easily access and attach themselves on the salmonids. Salmon lice have previously been one of the most critical problems found in the industry, as it disturbs and physically damages the fish. The annual expenses of combating salmon lice have accumulated to 2 to 3 billion NOK (Iversen et al. (2015)). This includes expenses associated with different combating strategies and economic loss through lower feed conversion ratio and damaged biomass. Furthermore, lice may spread to the wild population and be transported to close aquaculture facilities.

Counting of lice are conducted weekly at water temperature above 4°, otherwise every other week. The counting is conducted by crowding the fish by use of float lines before a sample consisting of approximately 20-25 fish are withdrawn from the pens. The sample is investigated, counted and brushed. Delousing are initiated at:

- Nord Trøndelag and latitudes below
  - 0.2 lice per fish between week 16 and 21
  - 0.5 lice per fish between week 22 and 15
- Nordland, Troms and Finnmark
  - 0.2 lice per fish between week 21 and 26
  - 0.5 lice per fish between week 27 and 20

Combating lice may be done with different approaches, in which each approach has its advantages and disadvantages. The strategies differ between medical or mechanical treatment. Prior to the methods usually performed today, a chemical compound consisting of hydrogen peroxide was often used to remove fish lice. However, the mixture did affect the ecological environment and is today performed at a lower extent. The operation is performed by use of a closed tarpaulin that encloses the net. When the tarpaulin is mounted, the mixture of hydrogen peroxide is added. This operation usually requires four vessels; one carrying the chemicals, two assisting service vessels and one vessel with the responsibility of the tarpaulin mounting. The use of vessels equipped with cranes may introduce complications, as strong cranes might tear the net if not carefully operated. Further medical treatments can be conducted by adding medicine in the feed for a couple of weeks.

Mechanical treatment of fish lice involves pumping the fish on-board a vessel or a barge where it is exposed to warm water or chemicals before departing it back in the pen. This process is efficient, yet disturbing for the fish, as fish is sensitive to physical handling. Instruments such as Thermolicer and Optilicer are usually used for these processes, which is far more friendly to the environment compared to the aforementioned approaches.

An environmentally friendly method of deploying cleaner fish which lives in symbiosis with salmon is a good solution too (Skiftesvik et al. (2013)). Through correspondence with Langøylaks AS, it was found that companies with a successful strategy regarding the use of cleaner fish initiate delousing twice during a generation. Other companies which do not utilise cleaner fish might delouse more frequent during a generation.

2.3.5 Collecting of dead fish

Deceased fish are periodically removed from the bottom of the cage by the use of dead fish collectors. It is important to inspect and count the dead fish to recognise eventual patterns of mortality, as variations might indicate an outbreak of diseases. In addition, keeping track of mortality is essential in terms of estimating the final output. LiftUp is a device that is widely utilised in Norway, which has a basket that rests on the bottom of the net. By use of pumps it automatically circulates dead fish from the bottom to shore or a barge. It may be removed or relocated by the use of cranes, hand or a balloon. It must be removed prior to crowding of fish associated with delousing, harvesting and occasionally during the counting of lice. Hazards around such collectors are excessive weight, surface contact or entanglement between the device and net. In general, the device is safe to use and has low initial weight, but has been subject to hole inducing accidents.

2.3.6 Challenges within Aquaculture Operations

Operators conduct daily work on remote, unstable foundations exposed to wind, current and waves. Cold temperature and darkness further complicate the labour which otherwise would be done easily. The harsh conditions reduce human cognitive abilities, further increasing the risk of conducting mistakes. Harsh conditions itself are a risk to the system as severe weather might damage the system. Additionally, severe conditions can cut accessibility to the pens in which inspections are unable to be executed. Wear and tear from the weather may then remain undetected. The perception of bad weather differs from localities, as the farm systems usually are dimensioned accordingly to their respective locality investigations.

Operations in-shore require benign weather conditions and are often initiated based on experience. This introduces complications as weather windows might often be limited, pressuring the operators and managers to undertake critical measures impulsively to avoid undesired accidents. In addition, the nature of an aquaculture's infrastructure complicates the opportunity to directly receive or give aid, forcing the operators to be solely responsible for all the practical safety decisions in the field (Utne et al. (2015)). If strong winds or waves occur during operations, the work should be cancelled immediately to ensure the safety of personnel. Surveys show that there is a low threshold of discontinuing the labour if operators wish so. Regarding fish escape, surveys indicate that workers may put aside personal safety to intervene in an incident to ensure no fish escape (Thorvaldsen et al. (2015)).

Furthermore, workers usually work from morning until evening. Long working hours and understaffing are contributing factors for fish escape. Understaffing increases the total workload of the present workers. For intensive and long operations, such as lice treatment, for instance, shifts may be divided among internal employees and/or hired labour to avoid fatigue. However, issues regarding obtaining well competent and qualified personnel is a well-known challenge. The workers should be familiarised with the farm, procedures, and tools to avoid unnecessary incidents. Crucial elements to master are the ability to execute tasks safely and competence to safely handle critical situations as they arise. Thorvaldsen et. al. conducted a survey in 2016 to investigate the practices in aquaculture in terms of HSE, in which 94 % agreed they had the competence to perform tasks safely. Additional parameters to consider are planning the schedule ahead, as optimism regarding operation length should be avoided. The pressure to finalise an operation might reduce the quality of work and personal safety. It was found that 21.5 % of workers experience a stressful environment quite often (Thorvaldsen et al. (2016)). The top management has the ability and responsibility to avoid suboptimal conditions for the workers to ensure success in operations.

As stated, personnel should be qualified to work on fish farms. Insufficient competence, training, and experience are a source of mismanagement of the physical system which can result in a fish escape. Almost everything in the physical system is located underwater, which empathises the importance of being familiar with different potential failure configurations. Thus, fish farmers are very alert and aware of the consequences. Situational awareness and prediction are key abilities to prevent accidents or cancelling work if it's too dangerous to continue. Surveys indicate that 86 % of workers will inform and stop their colleagues if they observe dangerous behaviour at work (Thorvaldsen et al. (2016)). Source of dangerous work to personnel is handling of equipment such as cranes without proper training or during harsh weather. Therefore it is preferred to assign tasks that are not performed often to an experienced operator. Regarding training and formal education in aquaculture, it is desired that workers have obtained a certificate of apprenticeship. It is however not required, but certain companies may cover the expenses for obtaining certificates for employees. Recruited personnel are required to receive training from an experienced colleague before gradually taking a more active and responsible position. Besides training individuals, several companies offer internal courses such as workshops. The topic of relevance has been fish escapes, safe operations, and best practices to enhance attitude, awareness, and culture. (Thorvaldsen et al. (2015))

Communication in the field has proven to be a challenge. Several actors with no prior knowledge of each other may cooperate to carry out extensive tasks. Usually, authority is divided among the farm operational manager and the captain of service vessels. A shared understanding of the operation and proper delegating of responsibilities beforehand are essential for safe operations. Clarification of operational tasks prior to execution can be done at startup meetings. In addition, the crew may familiarise themselves with each other at these meetings, which is a positive contribution to the working environment.

The research focus upon matters of health, environment, and safety within aquaculture is stated to be an area of improvement, as the research has mostly been oriented around how to ensure fish welfare and structural integrity. Aquaculture is one of the most hazardous occupations in Norway, with 1400 reported injuries from 1988 to 2013 and 33 fatalities from 1982 to 2013. Examples of injuries are cuts, slip, and fall, crushing, hypothermia, chemical burns and hearing loss (Holen et al. (2017)). Fortunately, there is observed a decrease in the number of fatalities and injuries in the last decade (Utne et al. (2015)). Aquaculture companies are required to comply with the internal control of health, safety and work environment. This implies that companies are obliged to work systematically to improve the performance of health, safety, and environmental policies. Furthermore, this includes obligatory documenting of planning, organising, and implementations of measures that shall be available to workers. This is the basis of the safety management system in aquaculture. The Norwegian Labour Inspectorate Agency is responsible to assess the documentation during inspections, which is a valuable asset for accident investigations (Holmen et al. (2017)).

2.4 Safety Management in Aquaculture

Proactive approaches to ensure a safe environment for workers and the prevention of fish escape are formalised through the safety management system. Safety management systems in aquaculture consist of safety procedures, risk assessments and non-compliance reports (Thorvaldsen et al. (2015)). To establish a safety system that meets the requirements set by the regulatory authorities while coordinating internal procedures is a challenging task. Ruling authorities do not have an integrated system across the different instances, which lowers the threshold of conducting insufficient risk assessments and reporting non-conformity to the relevant parties. Therefore, the evolution of safety management systems recognises how respective enterprises manage risk by internal policies, risk analysis and up-following control measures (Holmen and Thorvaldsen (2018)). The system is an important initiative within organisational safety that introduces barriers.

Audits are used to assess the performance of the system subject to external and internal requirements. These may be conducted internally or through third-party companies issued by Norwegian Accreditation. Certifications received by accredited third parties indicate that the company meets the requirements defined in the standards (Holmen et al. (2017)).

This section presents how safety is conserved in the aquaculture industry. Initially, the reader will be introduced to the existing regulations which affect the operational and structural context of the industry. Secondly, initiatives regarding safety management in aquaculture are presented.

2.4.1 Legal Conditions

The Norwegian aquaculture industry is regulated by five authorities; Directorate of Fisheries, County Governor, Food Safety Authority, Norwegian Maritime Authority, and the Norwegian Labour and Inspection Agency. The Norwegian Ministry of Fisheries and Coastal Affairs govern the regulations and the different authorities have executive power within their respective fields of interests.

The components that constitute the physical fish farm system are regulated by Regulation on Technical Requirements to Floating Aquaculture Installations (FOR-2011-08-16-849)

(NMTF (2011)). This regulation is usually called NYTEK and is further addressed in Section 2.4.1.1. Alongside the Aquaculture Act (NMTF (2005)), this regulation is governed by The Directorate of Fisheries.

Further, the Regulations on the Operation of Aquaculture Facilities (FOR-2008-06-17-822) (NMTF (2014b)) aims to preserve the welfare of marine species during breeding. The Food Safety Authority has the management responsibility within this area. The purpose of the regulation is to enhance the profitability and competitiveness of the industry by ensuring sustainability and value generation along the Norwegian coast.

The Norwegian Maritime Authority administers the vessels involved in aquaculture operations, in which Regulation on Construction and Supervision of Small Cargo Ships (FOR-2014-12-19-1853) (NMTF (2014a)) applies. This regulation requires testing and documentation of stability and capabilities of vessels involved in towing, crane operations and anchor handling. Note that this does apply to vessels between 8 and 24 metres in length, with exception to vessels below 15 metres in length that are not involved in any aforementioned operations.

2.4.1.1 NYTEK & NS 9415:2009

Regulation on Technical Requirements to Floating Aquaculture Installations (FOR-2011-08-16-849) is an official regulation for technical requirements for floating aquaculture facilities, which it refers to the Norwegian Standard 9415:2009, or alternatively an international standard with equivalent technical safety level. It was introduced by Norwegian Ministry of Fisheries and Coastal Affairs in 2003 after several incidents of fish escape to secure a satisfactory technical level on fish farms in Norway. The regulation requires that site surveys, mooring system analyses and components used in aquaculture facilities have to be accredited, i.e. accredited by an official accreditation company issued by Norwegian Accreditation. The requirement set in the regulations has to be met to receive a production certificate.

NS 9415:2009, alongside with NYTEK, has contributed to more advanced technical standards in aquaculture, with lower occurrences of fish escapements in the years following their implementation in 2003. NS 9415:2009 sets requirements for the design, dimensioning, production, installation, and operation. In addition, it defines guidelines for site surveys prior to deployment and calculation of environmental loads. The motivation for establishing this standard is primarily to reduce the risk of fish escape as a consequence of technical failure. NS 9415:2009 is itself not statutory, but statutory through NYTEK (FOR-2011-08-16-849) (NMTF (2011)).

Following the implementation of statutory requirements such as NS 9415:2009 and NYTEK there has been achieved a significant reduction in both occurrence and quantity of escapees the last decade. The results of statutory standards that apply to the technical aspect at a facility confirm the impact of the actions, especially when taking the growth of biomass into consideration. However, the results might imply that current issues regarding fish escape arise from incorrect handling and management of the physical system itself. Therefore it is important to address organisational and human issues to eliminate the organisational risk factors which lead to human error (Holmen et al. (2017)). Human error is inevitable but can be reduced to an extent through well-defined procedures based on analyses of the farming system.

2.4.2 From Policy to Implementation

Ensuring smooth implementation of formalised policies is essential for a successful safety management system. To create an efficient safety management system, the issues should be addressed by the involved parties. By acknowledging the issues themselves, there is no better actor to ensure developed measures that suit respective farms. Considering the dramatic changes regarding aquaculture technology, there must exist a correlation between the procedures and the current practices.

2.4.2.1 Risk Assessments

It has been observed that improper risk assessments of the farming system have led to fish escape. Risk assessments are utilised in aquaculture, and other industries likewise, to raise awareness of hazards and to reduce the likelihood and impact of these. Barriers are the term for measures that are implemented to prevent or mitigate hazardous events. Companies conduct assessments as a part of the internal control to plan risk treatment during production processes and operation. In Norway, operators and workers are obliged to be involved in risk consideration processes to ensure that identified areas of risk can be farm specific and understood. Furthermore, companies should document risk-reducing initiatives such as risk matrices and acceptance criteria. Findings indicate companies usually utilise qualitative approaches with colourised acceptance criteria in the matrices. Green indicates acceptable risk, yellow indicates measures should be considered and red unacceptable risk with necessary measures required (Holmen et al. (2018)).

Companies may conduct risk evaluations associated to tasks by the use of a Safe Job Analysis (SJA). This method is a simple analysis that identifies potential hazards prior to operations that is either unconventional or where dangers are anticipated. The process consists of several steps where a chosen operation is evaluated by presenting suggestions for subtasks where hazards may be encountered. Certain companies have created their own SJA template in which can quickly be utilised at meetings prior to the operation to create a shared understanding of the risks. Templates can increase the efficiency of risk assessments since possible dangers are already stated. Thus, a thorough template can be used as a checklist that applies to a variety of operations. Surveys show that 98.3 % of fish farms have conducted a risk analysis during the last four years. Furthermore, SJA has been utilised by 90.2 % of fish farms during the same time (Kongsvik et al. (2018)).

2.4.2.2 Procedures for Safety

Procedures are involved in different aspects of fish farming. Examples are safety procedures, which may require contingency planning and the use of protective clothing. In addition, it may deny fatigued workers from executing tasks. Furthermore, maintenance and inspection procedures ensure a proper state of equipment during production and operational phases. For instance, an inspection of the net by divers or ROVs is required after changing the net or relocating the sinker tube. Procedures within the operational context present the methods for certain operations and which equipment is appropriate to use in operators manual. Companies are required to document the procedures as part of their internal control.

Deviations from procedures can single-handedly contribute to fish escape, near-misses and create a hostile working environment. Noncompliance reports indicate that previous escapees have resulted from not following the procedures or by not having any procedures at all. Discrepancies may occur if fish farm operators perceive a practical solution to be more efficient than the method stated in the operators manual. This may happen if the procedures are simple and standardised or if the author of the procedures is not familiar with the farm itself (Thorvaldsen et al. (2015)). However, applying a quick solution that deviates from the norms might not be effective in the long run, as it creates a mindset that encourages efficient but unsafe work. Apprentices may learn that rules are not necessarily always applicable by observing experienced personnel behave this way.

Likewise, as with risk assessments, the establishment of procedures should be conducted through cooperation with managers and farm operators. Surveys show that 61 % of operators were involved in creating new safety procedures. However, it was also found that 40 % felt that safety procedures could be vague and hard to understand (Kongsvik et al. (2018)). This can be countered by engaging farm workers to a larger degree. By developing the procedures with operators who actually execute the tasks and are familiar with the risks, best practices and comprehensive explanations of procedures will to a larger extent be well written.

2.4.2.3 Noncompliance Reports

Noncompliance reports are issued whenever a farm worker or manager experience failure towards meeting a regulatory requirement. The purpose of these reports is to describe the context of the deviation and are a useful tool to implement new measures and practices. Studies indicate that companies consider noncompliance reports seriously and as a useful asset. However, it was found that the perceived importance of noncompliance reports may vary among employees depending on the significance of the nonconformity. 67 % have experienced nonconformity that was reported worthy but not further issued. This may occur if the simple problem is solved right away and workers would continue their tasks afterwards. Furthermore, 48 % expressed concern about using noncompliance reports as a basis to enhance the safety system was not utilised good enough (Kongsvik et al. (2018)). Operators have argued that in-field discussions regarding measures are just as efficient and have led to improvements (Thorvaldsen et al. (2015)). However, noncompliance reports to the regulatory authorities are mandatory and may be further utilised in research or by other companies to avoid the same mistakes.

2.4.3 Human and Organisational Factors

Employees are influenced by three factors at work - the organisation, tasks and personal factors. These factors aim to create a communication medium across the organisation to facilitate training systems and operational procedures to prevent human error. Human factors are usually used to describe and enlighten basic actions and sociotechnical interactions that may steer the outcome of incidents. One can distinguish between physical and psychological factors, in which the former include ergonomics, staffing, and competence. The latter describes human behaviour in terms of biological characteristics (Thorvaldsen et al. (2013)). Human error is the term used when a planned sequence of action fails to achieve its intended outcome. Human factors and error are often used in the same context but are divided by underlying causes (human factors) and immediate causes (human error) of accidents. Furthermore, human error may result from organisational decisions in which inappropriate practices occur (Skogdalen and Vinnem (2011)).

Organisational factors incorporate planning, organising, and distribution of assets, people, duties and training in coordinated activities to accomplish tasks. In that sense, the organisation has the ability to shape performance through culture, norms, communication, and rewards. Imperfect management of the organisational factors might be interpreted as organisational risk, in which Skogdalen and Vinnem (2011)) describes organisational risk as 'The risk of loss resulting from inadequate or failed internal processes, people and systems or from external events'. Organisational risk is widely included in risk assessments, and it is the organisations' way of accepting the fact that its management of personnel, processes and farm system are not always sufficient. The matter of trade-offs between cost efficiency and reduction in risk determines the potential losses companies are willing to accept. For instance, hiring service and well boats for more than adequate time to ensure a margin of safety come at a large cost. In addition, expenses for continuous training of employees and investment in the newest and safest technology are controlled and decided by the management.

Technical development has progressed vastly since the pioneering era of aquaculture, in which technical and functional challenges have continuously been met. Technology has simplified a variety of operations by use of cranes, fish collector, and feeding systems. Despite new, enhanced technology in the industry, research has found that suboptimal human-technology interface has led to the recent fish escapees (Thorvaldsen et al. (2015)). For instance, empowered cranes operated from vessels can introduce excessive loads from the boat and crane which can have an impact on the floating collar or tear the net if not carefully operated. The solution for the management is to increase the robustness of the system. Current fish farm systems are robust which implies that human and organisational factors are key parameters to consider when reviewing safety. This development has also been observed in other industries. Followingly, risk assessment has gradually included a larger diversity of aspects as viewed in Figure 2.2.

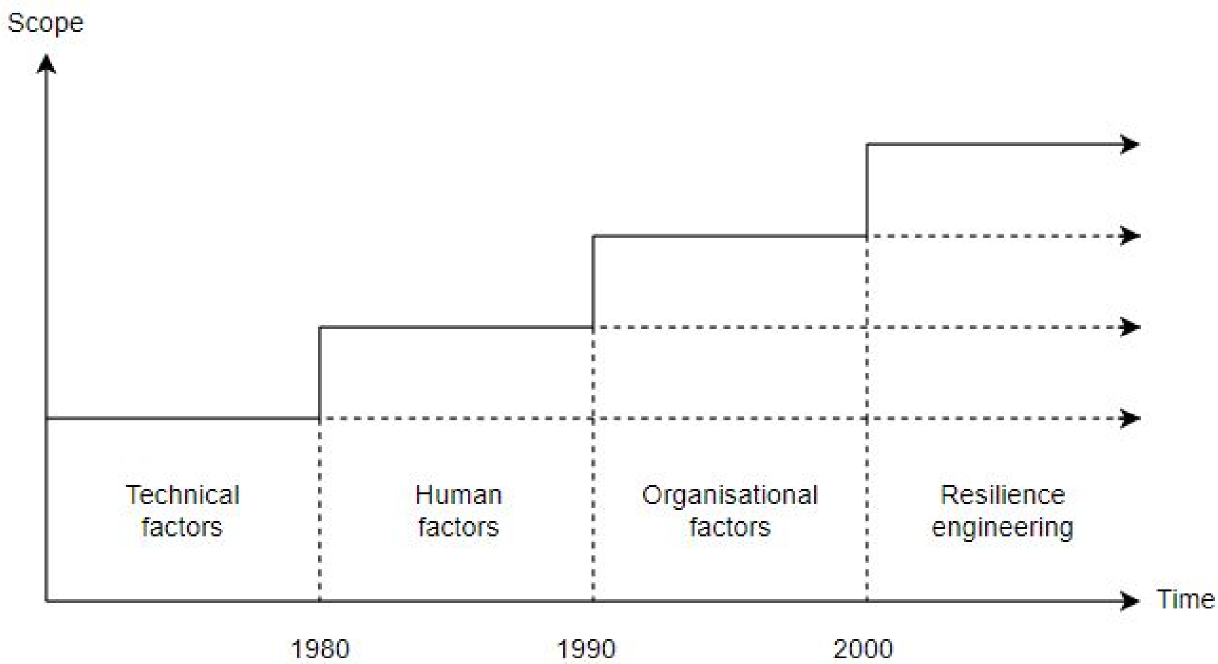

Figure 2.2: Gradual development of scope within generic risk assessment (Rausland and Utne (2007))

Robustness of the system may be achieved through resilience engineering, in which is defined as 'The intrinsic ability of a system or organisation to adjust its functioning prior to, during, or following changes, disturbances, and opportunities so that it can sustain required operations under both expected and unexpected conditions' (Hollnagel (2014)). Resilience engineering within aquaculture has introduced better performance standards, for example by the use of components with better properties and optimised mooring systems. The performance standard for organisational risk control is found to be measurable through a method called Operational Safety Condition (OSC).

OSC was developed to assess the efficiency of mitigating means of operational safety and is based on the Technical Condition Safety method used in the oil and gas industry. The term OSC is thoroughly described in the article *Organisational Safety Indicators: Some conceptual considerations and supplementary qualitative approach* written by Kongsvik et al. (2010), and applied to an aquaculture context in *Organisational Safety Indicators in Aquaculture - A Preliminary Study* by Holmen et al. (2017). OSC is a qualitative method based on information acquired through observations, conversations, and questionnaires of employees and documents. The findings are subject to further comparisons between the practical implementation of work procedures and formal safety requirements. Furthermore, this method can be used to develop safety performance indicators to evaluate technical conditions such as safety barriers, preventive measures or to satisfy regulatory requirements with respect to safety. This method is focused on human and organisational barriers in safety management.

Practically, OSC is composed of several steps. The initial parts involve mapping of the risk influencing factors, associated operations, and the organisational condition. The next steps are to identify associated internal and external requirements for the mapped conditions, and derive a checklist to determine whether or not the organisational practices meets the requirements. The final step is to conduct the audit to expose the strong and weak sides of the organisation to identify areas of improvement (Holmen et al. (2017)).

The state of organisational conditions can be implemented in risk models such as Bayesian Belief Networks by the use of organisational risk indicators (Rausland and Utne (2007)). These indicators can be determined by the management or be found through surveys and input from employees to quantify the impact an organisational condition has on the total organisational safety. For instance, consider a network that attempts to map the quality of work practices at fish farms. Variables that can be implemented is the perceived degree of compliance towards regulatory requirements for work practices. This can be measured through the quality of equipment, training, procedures and risk assessments. These organisational indicators can further be connected to work operations to determine the practical effects as illustrated in Figure 2.3.

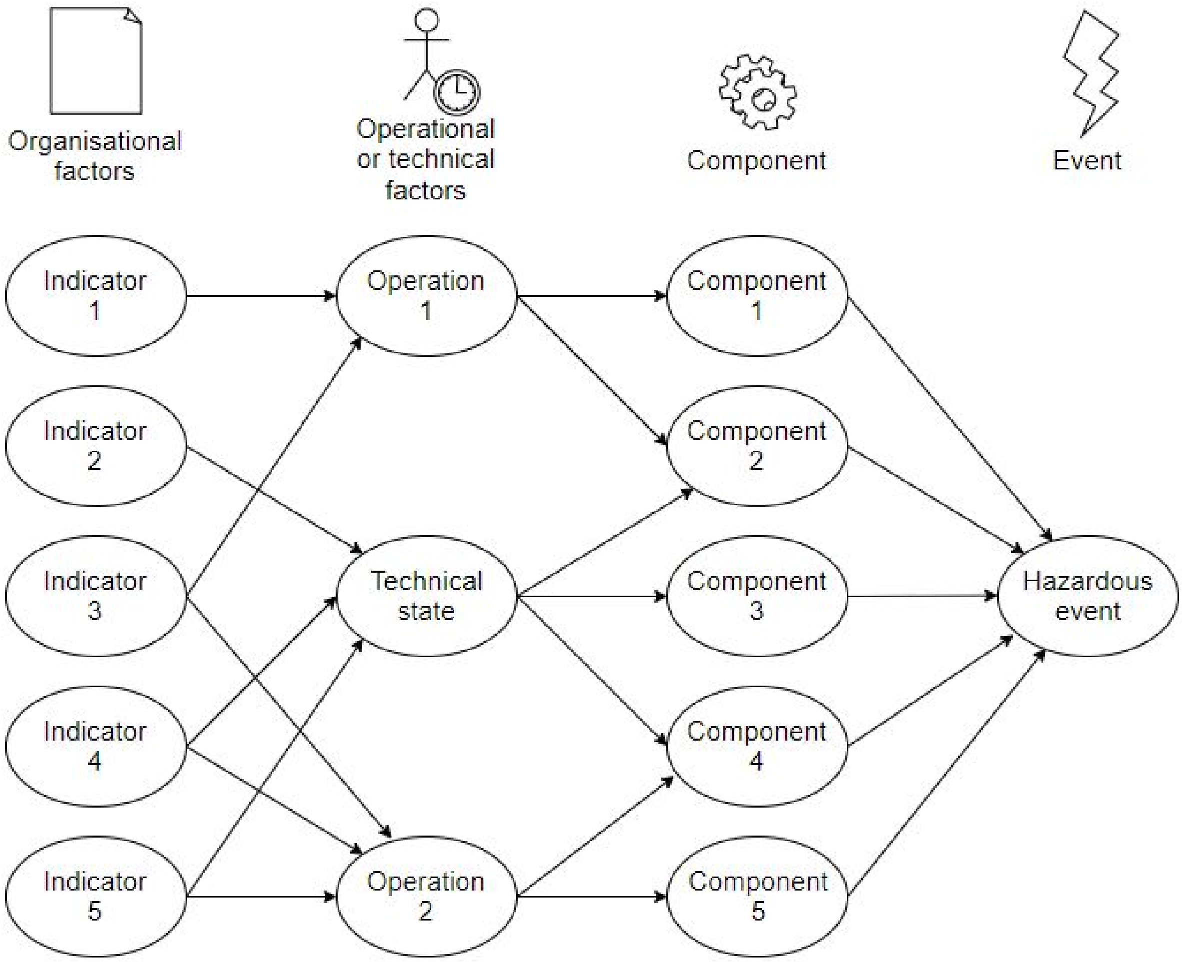

Figure 2.3: Qualitative model to map organisational risk (Øien (2001))

3 Data

3.1 Historical Data of Fish Escape

The context this thesis is built upon is respective reports of escapees, suspected escapees, and near-accidents of 2016 and an Excel database consisting solely of escapees from the period of 2010 to 2016, which the Directorate of Fisheries granted the author the permission to explore and utilise for this thesis. The respective reports were handwritten and had to be transferred to an applicable software where the information may be utilised, in this case, Excel was used to develop an additional database. To ensure consistency throughout both databases, the setup from the Directorate of Fisheries' database was adapted to the new one.

Regarding the respective reports, aquaculture companies are required to report every occurrence or suspicion of fish escape to the Directorate of Fisheries. Within a 24 hours period of escape, an initial report has to be submitted. The initial report often labelled as Part 1, has to present general information about the facility and specifications about the escape.

The second report, labelled Part 2, is required to be filed within one week after the incident. The purpose of Part 2 is to correct eventual discrepancies from Part 1, in addition to filling out the final details in the extent of the incident. The template from the Directorate of Fisheries is added in the appendices. The reader is encouraged to review the template before proceeding to obtain an understanding of which specifications the reports require.

Furthermore, The Directorate of Fisheries introduced a new online solution for reporting fish escape on 1. February 2019. The new approach aims to substitute the old approach of filing a paper-based report. Through correspondence with the Directorate of Fisheries' Communication Office, it was stated that this enabled a more consistent reporting system. The advantages are an enhanced filing system that enables a more rapid and fixed response for each respective accident. Furthermore, the digital reporting system eases the monitoring aspect which can further be utilised to obtain statistical properties of the industry. The application is friendly for mobile devices and can be reported from a smart-phone, which overall reduces paperwork and corrections. (Directorate of Fisheries (2019))

The Directorate of Fisheries performs an evaluation of each respective report of escaped fish (Directorate of Fisheries (2017)). The evaluations are based on the received reports from the site and independent inspections. Furthermore, by comparison, the reports issued by the Directorate of Fisheries are far more detailed and include further aspects such as compliance with statutory requirements and status of internal control for instance. The received reports are stored in a database and insensitive metadata regarding the escapees are posted publicly on the Directorate of Fisheries' website.

The public metadata displays a categorised distribution of causes of fish escape. The distribution is roughly divided within operational, structural, external causes. Further categories *not declared* and *not relevant* are included. The information is given in percentiles and quantity, but such input is not sufficient for further analysis. However, the Directorate of Fisheries possesses the authority to grant researchers and students insight into more sensitive data for analyses.

3.2 Database

The Norwegian national record of escapees is the most comprehensive of all aquaculture nations, spanning from 2001 to today. In this thesis, two databases are utilised to paint a picture of the current influential factors. The first database is created by the author from assessing every report submitted to the Directorate of Fisheries in 2016. These are mostly reports of suspected escapees and escapees of individual fish following an accident. Seven escapees of significant size were recorded in 2016 from in total 114 reports of escapees/suspected escapees. However, by filtering away escapes from farms that do not correspond to this thesis, 74 events are further considered. While this database does not possess many counts of actual fish escapees, it provides very useful input to understand how components and operations on fish farms might fail and lead to fish escape. Sufficiently many reports of suspected escapees are thorough and do to a large degree explain, for instance, how a hole has been created and could have led to fish escape. Most of these occasions have been intervened for in some way, or holes have been located outside of the fish's altitude where they thrive. By assessing these reports to create a database, a larger basis for comparison to see how integrity might be lost is created.

The second database consists solely of escapees in the period of 2010 to 2016 and is created by the Directorate of Fisheries. Combining these two databases allows for reviewing how the integrity is lost and the frequency for the different configurations for fish escape. The setup in both databases is similar, where the direct output for this thesis is based on pivot tables of direct, contributing and underlying causes. Pivot tables enable easy filtering between the different causes and are in general useful to capture a sequence of events behind a direct cause. Both rows of contributing and underlying causes are expanded to present sufficient information. Additional rows in the database summarise the event, describes the circumstances and presents implemented measures. Keywords, classifications of certain events and components are intentionally throughout the database used to ensure consistency and to enable the use of pivot elements.

The database is utilised to achieve the following purposes:

1. Identification of exterior cause(s) of fish escape
2. Identification of contributing and underlying causes
3. Identification of risk influencing factors associated with different configurations of fish escape
4. Adapt findings from 1. and 2. for implementation in Bayesian models to determine the degree of influence.

Questions or access to the database must be addressed to Ingrid Bouwer Utne.

3.2.1 Structure of the Database

In common for both database are additional rows which provide general information of the escapes or suspected escapees. Information such as date, locality, county, and company are presented. Further information about material type used for the pens, shore or land-based and fish species bred are displayed but are filtered away to correspond to this thesis scope. This scope comprehends only plastic fish farm types located in-shore which cultivates Atlantic Salmon. Additional information to recognise eventual patterns are presented through circumference and depth of pens, the weight of fish, the number of escapees and the number of re-catches. Table 3.1 displays classification intervals for escapes and plant design. The Directorate of Fisheries distinguishes between small, medium and large escapes, which is an indicator of how severe the escape incident is.

Table 3.1: Classification intervals for (a) number of escapees, (b) circumference for pens, (c) depth of net (Høyli (2016))

(a)

Category	Escapees
Small	≤ 999
Medium	1000 - 9999
Large	≥ 10000

(b)

Category	Circumference (m)
Small	< 95
Medium	95 - 130
Large	> 130

(c)

Category	Depth (m)
Shallow	≤ 15
Medium	16 - 30
Deep	≥ 31

Events are categorised following a predefined set of parameters which enables a swift adaptation of information from the report to the database. Specifically, the categorisation of events is subject to parameters that indicate the overall, direct, contributing and underlying causes. An example of a hole in the net is illustrated in Table 3.2.

Table 3.2: Categorisation of database

Overall cause	Direct cause	Contributing cause	Underlying cause
Structural	Hole in the net	Abrasion from ropes and weights	Faulty installation
Operational	Hole in the net	Handling of weights	Procedure not followed
External	Hole in the net	Flotsam	Harsh weather

The overall causes are divided into structural, operational and external causes. Structural causes are damage to the system caused by interactions between components and the net or failure of equipment. Operational causes are related to accidents occurring during operations, usually resulting from human error. External causes are damage caused by factors unrelated to the fish farm, for instance, flotsam, predators or maritime traffic.

Direct causes are primarily divided within a hole in the net and submersion of the net. Loss of fish is introduced as an additional parameter in the 2016 database, as numerous count of this parameter was found. Loss of fish involves escape of fish during physical handling or treatment.

Contribution factors are usually components or actions that are connected to cause the direct cause, often explained by underlying causes. Underlying causes may be wrongful installation, deviation of procedures or harsh weather.

4 Methodology

This section introduces the reader to the methods applied to this thesis. Firstly, the method used to interpret the findings in the database are presented and discussed. Secondly, the method of using Bayesian Belief Network to process the results are derived and discussed. Furthermore, three preliminary assessments of Bayesian models are presented.

4.1 Interpretation of the Database

The concept of probabilities and likelihood is widely used in risk and safety analyses. The purpose of utilising these concepts is to capture the frequency of undesired events or different configurations a system may be found in at a given time. Probabilities may be obtained through two methods; the frequency and the Bayesian approach.

The approach to obtain frequencies is based on the likelihood of a certain event occurring from a total possible number of events or during a time frame. Let $n_A(t)$ denote the recorded numbers of event A in which occurs during time t. The frequency during the time frame may be written as

$$f_t(A) = \frac{n_A(t)}{t} \tag{4.1}$$

This formula is applicable to the raw data in the dossier to obtain probabilities. To achieve credible estimations of frequencies, one has to take into account different parameters and variables in the calculations. Parameters such as the number of HDPE fish farms and pens, companies and licenses issued in Norway are taken into consideration. Further variables like frequencies of respective operations and count of escapees are also necessary to obtain correct frequencies. The goal is to obtain an output that determines the probability of a certain type of event for a single farm.

Assumptions have to be addressed for certain parameters and variables. According to the public metadata from the Directorate of Fisheries, there existed 3549 Atlantic salmon fish farms in 2016 in which 97 % was active (Directorate of Fisheries (2018)). The frequency of selected operations was obtained through research and correspondence with Langøylaks AS. A rough estimate applied to the entire aquaculture industry in Norway is displayed in Table 4.1.

Table 4.1: Estimated frequencies of operations

Operation	Comment	One pen /year	Norway /year
Net cleaning	Every 10th day	36.50	129 539
Counting of lice	Every 7th or 14th day	39.11	138 791
Delousing	Initiated at 0.2 or 0.5 lice per fish	8.00	28 392
Change of net	Every generation	0.67	2 366
Harvesting	Every generation	0.67	2 366
Crowding of fish	During delousing, counting of lice and harvesting	47.77	169 549
Relocation of dead fish pump	Delousing, net change, harvesting	12.50	44 363

However, the frequency interpretation assumes identical circumstances for every event which is not always realistic. Therefore, a Bayesian approach is advantageous to utilise in addition to the aforementioned approach. The Bayesian approach allows analysts to apply their subjective degrees of belief about an event. In this case, the probabilities do not necessarily have to be supported by large amounts of attempts or data but rather knowledge of the system. Furthermore, this method allows the modelling of conditional dependencies of events, enabling reviewing the corresponding relationships between risk influencing factors.

4.2 Bayesian Belief Network

Bayesian Belief Network (BBN) is an illustrative probabilistic method for modelling conditional dependencies. The method captures the Bayesian inference between variables derived from a conditional probability table. The network itself is a graphical, directed acyclic graph in which the arcs between respective nodes illustrates their conditional dependency. The conditional dependency, or conditional probability, is given by Bayes theorem, as stated in Equation 4.2.

$$P(A \mid B) = \frac{P(B \mid A)\, P(A)}{P(B)} \tag{4.2}$$

Bayes' theorem enables the user to update the belief about event A given information from another event B. Furthermore, $P(A)$ is defined as the prior probability of event A and should be distinguished from $P(A|B)$ which is the posterior probability of event A

given event B. $P(B|A)$ defines the likelihood of event B given event A. (Jensen (2007)).

For instance, let A be the parent of B, and the following equation $P(B|A)$ defines the causal relationship. However, B has an additional parent C, which do not interact with A. The parent nodes A and C is interpreted as unconditional, i.e. $P(A)$ and $P(C)$. Still, both A and C affects B. Thus, it is required to define B as $P(B|A, C)$. Here lies the strong and weak link within modelling of Bayesian Belief Network, as conditionally dependent variables are difficult to quantify but possible. Each event can be assigned a variable X_i with associated states if a quantitative approach is chosen. This variable determines the posterior probability of which system state the node is in given a set of relevant evidence. For the sake of simplicity, the set of states is often limited to two states, for instance, *Yes* or *No*.

To calculate the probability of the final event, i.e. our outcome, conditional probability tables (CPT) have to be derived and assigned to each node in the network. This information represents the likelihood of the event depending on prior events. A challenging task within Bayesian modelling is to limit the number of nodes, as the conditional table expands exponentially with the number of connected nodes. The current method of assigning conditional probabilities is based on the judgement of experts, estimates or statistical values obtained from data dossiers. The theory of local Markov property is applied to the network, which ensures that each node is independent of its non-descendant given predefined ancestor nodes. This property prevents illogical transitions between different system states. (Jensen (2007)).

In Norway, BBN is used in risk assessment with both quantitative and qualitative approaches. Qualitative methods can be used as a illustrative tool to obtain knowledge of relevant influential factors. The quantitative method is able to estimate the probability of an outcome given a predefined set of evidence, with easy identification of dominating risk influencing factors. The design of a network that applies the Bayes' theorem enables efficient creation of a domain consisting of models with uncertainty. The software GeNIe is in this thesis utilised to create the domain and to solve the calculations associated with the conditional probability tables. In addition, by using a graphical interface the software can easily demonstrate which risk influencing factors are present and how these affect the system through a sensitivity and strength of influence analysis. (Rausland and Utne

(2007)).

4.2.1 Preliminary Assessment for the Operative Model

The purpose of this BBN model is to capture identified risk influencing factors and the corresponding relationships between these which collectively may cause fish escape. The high-fidelity design of a representative network requires a defined design framework and sufficient knowledge upon the matter. Advantageously, the database is constructed in a manner that allows easy identification of associated influential factors. Consequently, the network created in this thesis is based on the findings from the database. Further elements, especially from a human and organisational perspective, could be included in the network illustrating how fish escape but are chosen to be modelled externally.

As the causal factors for fish escape are based on different operations and course of events, it may be advantageous to occasionally isolate the respective subgroups. This allows for grouping and measuring the variables for different configurations of failure which might lead to loss of integrity. Thus, the domain in which the network is built upon should be divided into five respective groups of risk correlations. This allows for distinguishing between the damage caused by external, structural and operational factors.

4.2.1.1 External factors

This subgroup displays variables representing how external factors may have an impact on the fish farm. The database has several counts of predators and flotsam causing holes in the net. To simplify the network, these two variables can be connected to one single node that represents the interaction between farms and external factors.

4.2.1.2 Structural abrasion

Abrasion as a subgroup illustrates how different components can induce holes in the net. The database has notable many counts of holes resulting directly from wear and tear from chains, weights, and ropes. Furthermore, this subgroup is affected by underlying variables such as weather, mistakes during the installation of components and mooring system issues. Additional variables as biofoul can increase abrasion as it alters the material properties, but it was not found any reports of this issue.

4.2.1.3 Rupture of net

This subgroup captures certain operations where the rupture of the net has occurred. Rupture of the net is strongly associated with activities where crowding of fish is conducted prior to the counting of lice, delousing and harvesting. Crowding of fish involves the use of float lines and re-positioning of weights. These components might have a rough surface or can be entangled in the net. Furthermore, the washing of net is an activity in which the rupture of the net has occurred several times. In general, these occurrences are linked to failure of following procedures.

4.2.1.4 Issues with vessels

This subgroup captures different issues associated with vessels, such as collision and propellers caught in the net. These issues have been seen to cause both holes in the net and submersion of the collar or net. These variables are strongly affected by the weather, technical failure and deviations of procedures.

4.2.1.5 Additional variables

The aforementioned subgroups are subject to natural stimulus from various factors that affect the variables. In this case, it was appropriate to include variables such as weather, mistakes during installation and deviations of procedures to design a holistic network of influential factors. Harsh weather introduces difficulties that increase the likelihood of abrasion, issues with the mooring system and operating of vessels. Abrasion and issues with the mooring system can be enforced by incorrect installation of components such as weights, ropes, and chains. Furthermore, the variable 'deviations of procedures' are added to review how the risk of rupturing the net increases or decreases as result of organisational status.

4.2.2 Preliminary Assessment for the Organisational Models

Besides assessing the causal factors for fish escape, it would be interesting to review how the safety management system is contributing to fish escape. Figure 2.3 in Section 2.4.3 illustrates how this can be achieved by mapping between organisational indicators, operational and technical factors, associated components and the hazardous event. The database provides enough input to map the latter nodes, but organisational indicators must be addressed and assigned by other means, for instance through use of OSC. Thus the first organisational network is intended to be qualitative to illustrate the deductive mapping process to understand how fish escape and how the organisation influences this.

For the second organisational network it was chosen to extract one of these organisational indicators to illustrate how it can be addressed and put into a network. The example in this thesis is a network that assesses influential factors leading to deviations from the procedures in the operational phase. The input variables are not a result of the database, but two surveys upon safety management and health, environment, and safety in aquaculture conducted by Kongsvik et al. (2018) and Thorvaldsen et al. (2016). Obtained information and results are displayed in Table 4.2. The questionnaires reflect the employees' perception of their own working environment. Regarding the survey of the safety management system, the answers reflect the employees' agreements or disagreement towards the question, with 100 % indicating strong agreement.

Table 4.2: HMS and Safety Management survey

HMS Survey		Safety Management Survey	
n Companies	40	n Companies	15
n Employees	447	n Employees	135
Operator	57.7 %	Managing Director	13.3 %
Manager	24.6 %	Department manager	10.4 %
Service vessel employee	13.4 %	Chief Operating Officer	20 %
Other	4.3 %	Operator	11.8 %
		HR Manager	6.7 %
		HES Manager	6.7 %
		Production Manager	7.4 %
		Site Manager	15.6 %
		Quality Manager	5.9 %
		Do not wish to answer	2.2 %

Experience		Experience	
0 - 2 years	13.6 %	< 1 year	3 %
3 - 6 years	23.9 %	1 - 2 years	5.2 %
7 - 14 years	24.2 %	3 - 6 years	18.5 %
15 years or more	38.3 %	7 years or more	73.3 %

Results		Results	
Stress are experienced often	21.5 %	Perceived quality of safety management system is good	79 %
Insufficient rest are experienced often	13 %	Sufficient staffing to achieve good safety level	72 %
Employees uses required safety wear	92 %	Procedures are vague and hard to understand	40 %
Informing if observing dangerous situations	85 %	Employees are familiar with procedures	92 %
Stopping colleagues if observing dangerous behaviour	86 %	Risk assessment has been conducted during the last four years	98.3 %
Stopped by colleague if working outside safety boundaries	92 %	Active use of Safe Job Analysis	90.2 %
Stopping work if too dangerous to continue	93 %	Active use of risk analyses	81.4 %
Competence to execute tasks safely	94 %	Involving employees in risk evaluations	86 %
Competence to handle critical situations	77 %	Priority of production over personal security	23 %
Workers involved when new procedures are implemented	78 %	Production requirements can lead to deviation of procedures	36 %
Workers involved when creating new procedures	67 %	Not following safety rules in general production	23 %
Workers involved when buying new equipment	75 %	Not following safety rules in potential dangerous operations	16 %

This approach addresses human and organisational aspects to review how safety management should be improved. Chosen parameters from the surveys are used to assign values in the conditional probability tables. The purpose of creating this network is to review how qualitative approaches, such as OSC, can applied to create networks so the management and operators can use this to assess the organisational conditions. In this network it is advantageous to occasionally subgroup the variables, in which the first subgroup interprets the quality of the safety management system. The second subgroup reviews the state of worker's competence in safety work.

4.2.2.1 Quality of the Safety Management System

This subgroup reviews how workers are involved in decision processes and the perceived quality of the management system. The variable which assesses the involvement of employees is the descendant of three variables that captures their perception of the impact they have to influence the working environment. These variables describe the involvement of workers when ordering new equipment, creating new procedures and the implementation of these. Furthermore, the involvement of employees in risk assessments is included as a variable. By involving employees in the processes to enhance the safety management system, the management can ensure the system corresponds to the actual practices.

4.2.2.2 Safety level during operations

This subgroup captures the perceived competence towards safe work practices among employees. The variables descend into a variable that captures to which degree employees continue to work outside of safety boundaries. The influential factors are how competent employees are to execute tasks safely, to handle critical and dangerous situations. Additionally, it was found that a noticeably high amount of employees agreed that production requirements lead to deviations of procedures. Furthermore, the weather is included as an additional variable to stimulate safety performance.

5 Results

5.1 Escapees 2010 - 2016

5.1.1 Interpretation of Database

Table 5.1 displays escapes from 2010 to 2016 divided in months. This is done to review potential seasonal influence.

Table 5.1: Escapes from 2010 to 2016 divided in months

Month	Events	Total escapees	% of total escapes	Average per escape	Maximum	Minimum
January	3	33 299	2.8 %	11 100	23 238	1 231
February	3	229 357	19.3 %	76 452	173 156	9 158
March	0	0	0	0	0	0
April	2	154 942	13.1 %	77 471	119 942	35 000
May	2	66 704	5.6 %	33 352	41 904	24 800
June	2	1 650	0.1 %	825	1 000	650
July	3	16 425	1.4 %	5 475	8 661	2 000
August	2	74 811	6.3 %	37 406	48 319	26 492
September	9	63 172	5.3 %	7 019	26 673	1 415
October	8	163 146	13.8 %	20 393	76 170	900
November	10	269 930	22.8 %	26 993	60 528	500
December	10	112 659	9.5 %	11 266	68 000	500
Total	54	1 186 095	100.0 %	25 646		

Table 5.2 displays the parameter assessment for escapes, based on the defined intervals in Table 3.1, Section 3.2.1.

Table 5.2: Parameter assessment for escapes from 2010 to 2016

Escape quantity	Events	%
Small	4	7 %
Medium	27	50 %
Large	23	43 %
Unknown	-	-

Circumference	Events	%
Small	5	9 %
Medium	11	20 %
Large	27	50 %
Unknown	11	20 %

Depth of net	Events	%
Shallow	22	41 %
Medium	12	22 %
Deep	8	15 %
Unknown	12	22 %

Table 5.3 categorises the causal factors for fish escape from 2010 to 2016. The table displays two events leading to fish escape; hole in the net and submersion of net. These have resulted from a variety of structural, external and operational causes.

Table 5.3: Escapees 2010 - 2016

Cause	Hole in net			Net submerged		
	Events	Total escapes	% of escapees	Events	Total escapes	% of escapees
Bottom ring chains	6	165 009	13.91 %	-	-	-
Dead fish pumps	4	109 326	9.22 %	-	-	-
Predator or flotsam	2	18 983	1.60 %	1	2 020	0.17 %
Vessels	4	63 304	5.34 %	2	4 353	0.37 %
Feeding barge	1	60 528	5.10 %	-	-	-
Handling of weights	7	250 211	21.10 %	-	-	-
Handling of net	5	18 161	1.53 %	2	3 000	0.25 %
Net cleaner	2	54 732	4.61 %	-	-	-
Mooring system	2	51 931	4.38 %	-	-	-
Collar submerged	-	-	-	2	120 592	10.17 %
Wear and tear from ropes and weights	4	76 790	6.47 %	-	-	-
Miscellaneous equipment	5	95 735	8.07 %	-	-	-
Insufficient fixing of net	-	-	-	2	30 243	2.55 %
Unknown	2	11 087	0.93 %	1	50 090	4.22 %
Total	44	975 797	82.26 %	10	210 298	17.73 %

Figure 5.1 displays recorded events of fish escape between 2010 and 2016, and the amount of fish escaped for each respective event. Since the timeline is long, the distribution is divided in months.

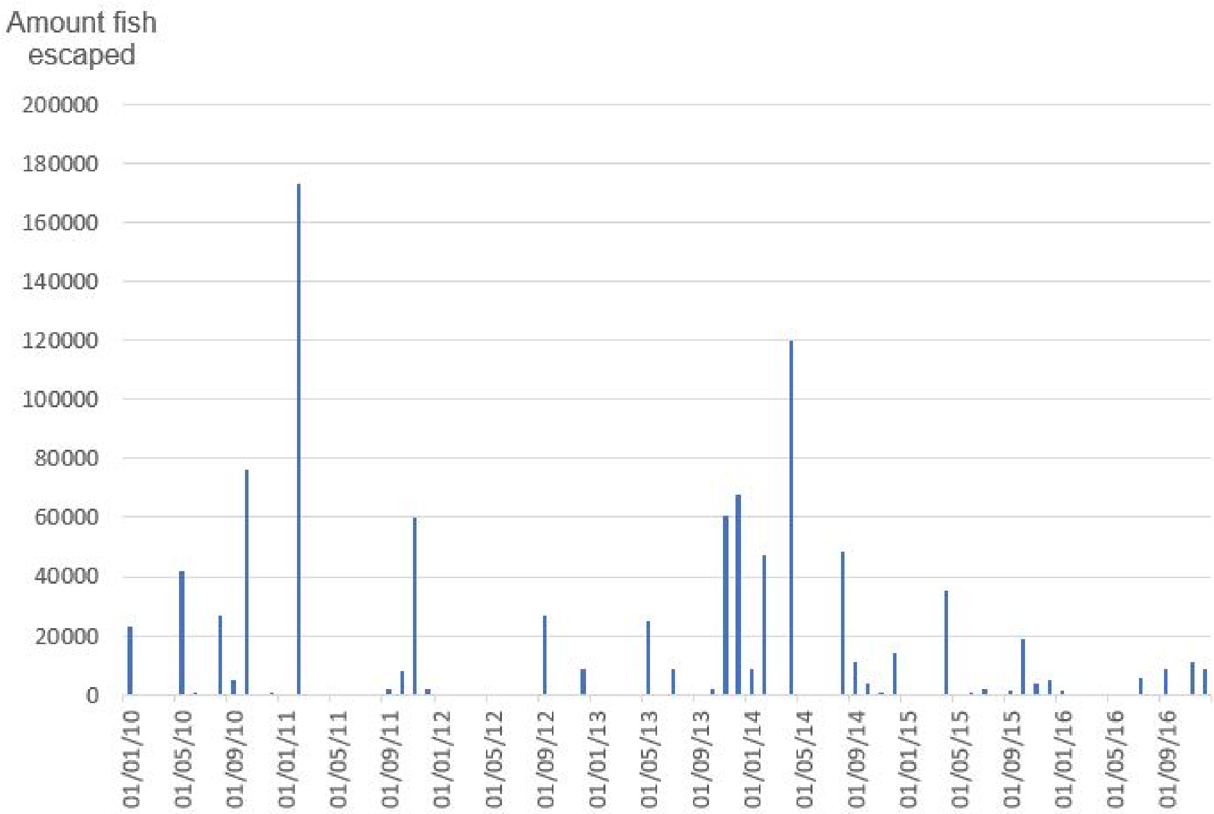

Figure 5.1: Amount fish escaped during 2010 - 2016

5.2 Suspicion and Escapees in 2016

5.2.1 Interpretation of Database

Table 5.4 displays escapes in 2016 divided in months. It also displays the percentage of which are actual escapes.

Table 5.4: Escapes in 2016 divided in months

Month	Events	Events with escapes	Total escapees	% of total escapes	% of events are escapes	Average per escape	Maximum	Minimum
January	7	1	1231	3.0 %	14 %	1231	1231	1231
February	11	4	94	0.2 %	36 %	24	60	5
March	0	0	0	0 %	0 %	0	0	0
April	6	1	1	0.0 %	17 %	1	1	1
May	2	2	16	0.0 %	100 %	8	15	1
June	3	2	13	0.0 %	67 %	7	10	3
July	7	2	5765	14.0 %	29 %	2883	5764	1
August	10	2	16	0.0 %	20 %	8	15	1
September	6	2	11691	28.5 %	33 %	5846	8753	2938
October	8	2	90	0.2 %	25 %	45	50	40
November	8	2	10771	26.2 %	25 %	5386	10766	5
December	6	3	11393	27.7 %	50 %	3798	8420	13
Total	74	23	41081	100.0 %	31 %	1786		

Table 5.5 displays the parameter assessment for escapes, based on the defined intervals in Table 3.1, Section 3.2.1.

Table 5.5: Parameter assessment of escapes in 2016

Escapes	Events	%
Small	16	22 %
Medium	6	8 %
Large	1	1 %
Without escapes	51	69 %

Circumference	Events	%
Small	2	3 %
Medium	9	12 %
Large	48	65 %
Unknown	15	20 %

Depth of net	Events	%
Shallow	15	20 %
Medium	30	41 %
Deep	14	19 %
Unknown	15	20 %

Table 5.6 categorises the causal factors for fish escape in 2016. The table displays two events leading to fish escape - hole in the net and submersion of net. The table follows the same layout as Table 5.3 with additional columns to distinguish between events with and without escapes.

Table 5.6: Escapees and suspected escapes 2016

Cause	Hole in net				Net submerged			
	Reported events	Events w/ escapes	Total escapees	% of escapes	Reported events	Events w/ escape	Total escapees	% of escapes
Bottom ring chains	2	1	1 231	3.00 %	-	-	-	-
Dead fish pumps	10	4	5 788	14.09 %	-	-	-	-
Predator or flotsam	12	0	0	0	-	-	-	-
Vessels	2	1	10 766	26.21 %	2	1	2 938	7.00 %
Feeding barge	-	-	-	-	-	-	-	-
Handling of weights	3	2	8 753	21.31 %	-	-	-	-
Handling of net	8	1	8 433	20.53 %	-	-	-	-
Net cleaner	14	0	0	0	-	-	-	-
Mooring system	-	-	-	-	-	-	-	-
Collar	-	-	-	-	-	-	-	-
Wear and tear from ropes	7	2	2 975	7.24 %	-	-	-	-
Miscellaneous equipment	3	0	0	0	-	-	-	-
Insufficient fixing of net	-	-	-	-	-	-	-	-
Unknown	-	-	-	-	-	-	-	-
Total	61	11	37 946	92.36 %	2	1	2 938	7.15 %

Table 5.7 displays additional causal factors for fish escape in 2016. The table accounts for loss of fish, with its cause and associated operation.

Table 5.7: Loss of fish in 2016

Cause	Associated operation	Reported events	Total escapes	% of escapes
Flooding of container	Delousing	1	20	4.87E-04 %
	Counting of lice	1	3	7.30E-05 %
Wrongful translation	Delousing	4	155	3.77E-03 %
	Counting of lice	3	3	7.30E-05 %
	Dead fish pump	1	1	2.43E-05 %
Sorting of fish	Miscellaneous equipment	1	15	3.65E-04 %
Total		11	197	4.80E-03 %

Figure 5.2 displays recorded events in 2016, and the amount of escaped for each respective event. There is observed seven notable events and several minor incidents.

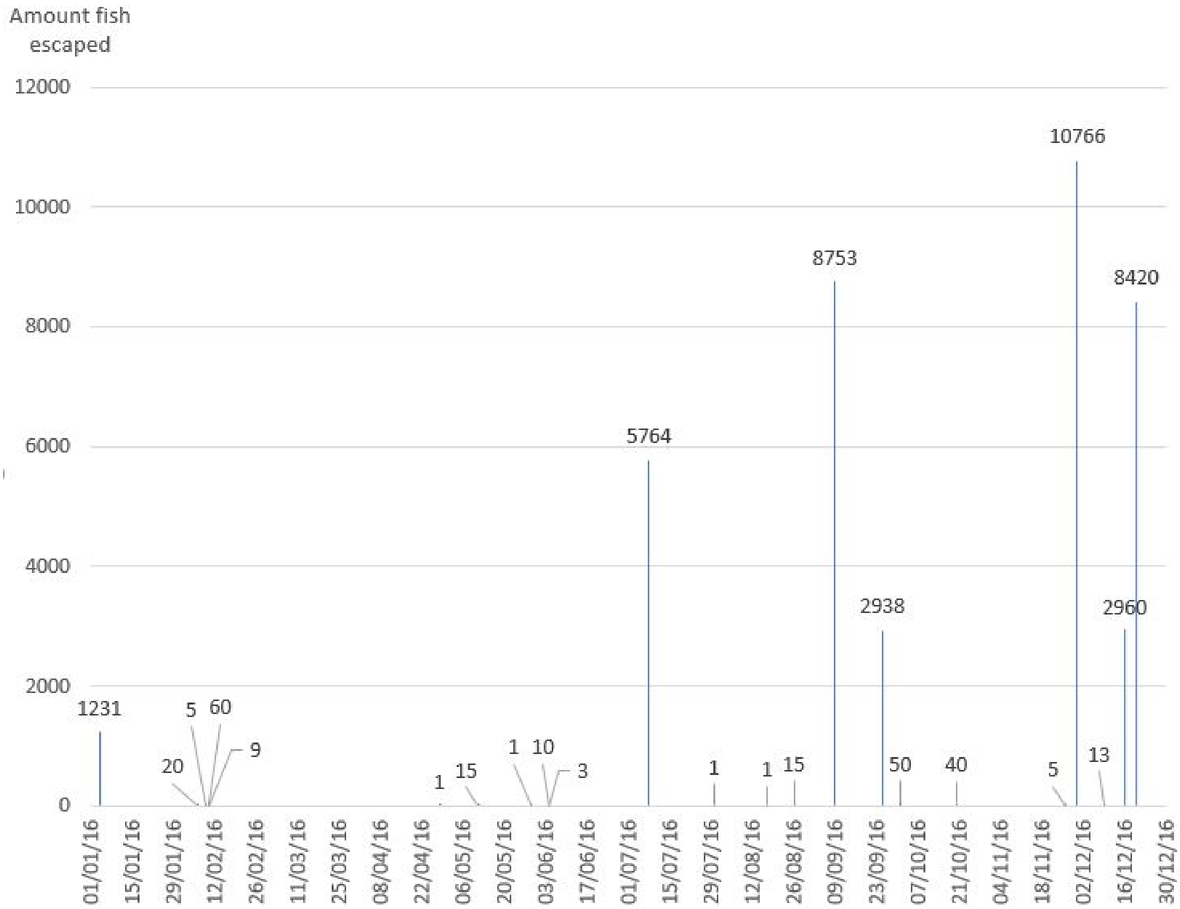

Figure 5.2: Amount fish escaped in 2016

5.3 Categorised Events with Estimated Frequencies

Table 5.8, 5.9 and 5.10 categorises different causes of fish escape, with contributing and underlying factors. The tables are created following the setup found in the database, as illustrated in Table 3.2, Section 3.2.1. Frequencies are estimated by use of the identified frequencies of operations which is given in Table 4.1, Section 4.1.

Table 5.8: Fish escape resulted by operational causes

Operational causes						
Direct cause	Contributing factor 1	Contributing factor 2	Underlying cause 1	Underlying cause 2	Frequency per farm	Frequency Norway
Hole in net	Dead fish system	Wrongful installation	Interaction between net and equipment	Harsh weather	2.88E-06	2.82E-03
Hole in net	Handling of net	Float line	Entanglement	Procedures not followed	5.43E-08	5.31E-05
Hole in net	Cleaning of net	Use of RONC	Twines damaged	Worn net	1.11E-07	1.08E-04
Hole in net	Vessel	Propeller in net	Slack net	Harsh weather	1.44E-07	1.41E-04
Hole in net	Handling of weights	Raising/lowering of weights	Procedures not followed	Insufficient training	1.81E-08	1.77E-05
Hole in net	Wear and tear from rope and weights	Wrongful installation	Tight rope	Harsh weather	5.76E-07	5.64E-04
Net submerged	Handling of net	Change of net	Procedures not followed	Insufficient training	1.44E-07	1.41E-04
Net submerged	Vessel	Collision	Traffic	Harsh weather	5.76E-07	5.64E-04

Table 5.9: Fish escape resulted by structural causes

Structural causes						
Direct cause	Contributing cause 1	Contributing cause 2	Underlying cause 1	Underlying cause 2	Frequency per farm	Frequency Norway
Hole in net	Bottom ring chains	Interaction between net and chains	Wrongful installation	Harsh weather	5.76E-07	5.64E-04
Hole in net	Feeding barge	Interaction between feeding barge and net	Deviations in mooring system analysis	Harsh weather	4.80E-08	4.70E-05
Hole in net	Mooring and grid system	Interaction between bridles and net	Deviations in mooring system analysis	Harsh weather	4.80E-08	4.70E-05
Hole in net	Wear and tear from weights and ropes	Interaction between weights/ropes and net	Wrongful installation	Harsh weather	2.02E-06	1.97E-03
Hole in net	Dead fish pumps	Interaction between dead fish pumps and net	Wrongful installation, rough surface	Harsh weather	2.88E-06	2.82E-03
Net submerged	Collar damaged	Fire	Power supply to lights	Unknown	9.51E-08	9.30E-05

Table 5.10: Fish escape resulted by external causes

External causes						
Direct cause	Contributing factor 1	Contributing factor 2	Underlying cause 1	Underlying cause 2	Frequency per farm	Frequency Norway
Hole in net	External	Floatsam	Harsh weather		8.64E-07	8.45E-04
Hole in net	External	Predator	Dogfish, seal bluefin tuna		2.59E-06	2.54E-03
Hole in net	Vessels	Collision	Traffic	Harsh weather, darkness	9.60E-08	9.39E-05

The frequencies are estimated by use of data from 2016, with supplementary input from the 2010 - 2016 database whenever necessary. Certain events such as interaction between dead fish pumps and the net can be categorised as both structural and operational, as they are strongly connected to both causes and it is difficult to certainly classify it. Therefore, these events are displayed in both tables with same frequency. Furthermore, escapes associated to loss of fish, as illustrated in Table 5.7, are not included as these events do not provide a basis for reviewing how fish escapes as a result of integrity loss.

6 Analysis

This section interprets the results to further investigate the causes of fish escape. Initially, an assessment of the findings from the database is presented. Secondly, the findings are implemented in Bayesian Belief Networks to determine the degree of influence on the risk of fish escape. Lastly, the influence of organisational risk is investigated qualitatively and quantitatively.

6.1 Analysis of Database

Figure 6.1 and 6.2 displays a distribution of categorised causes of escapes with the number of events within each category. Figure 6.3 and 6.4 displays the quantity of escapees within each causal category. Note that Figure 6.1 displays the accumulated amount of events, including events with and without escapes.

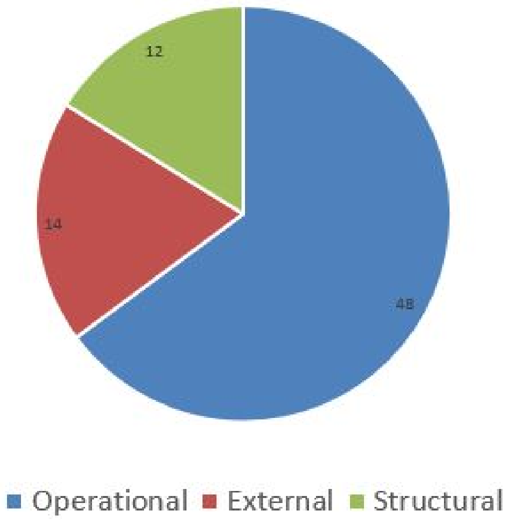

Figure 6.1: Causal factors 2016

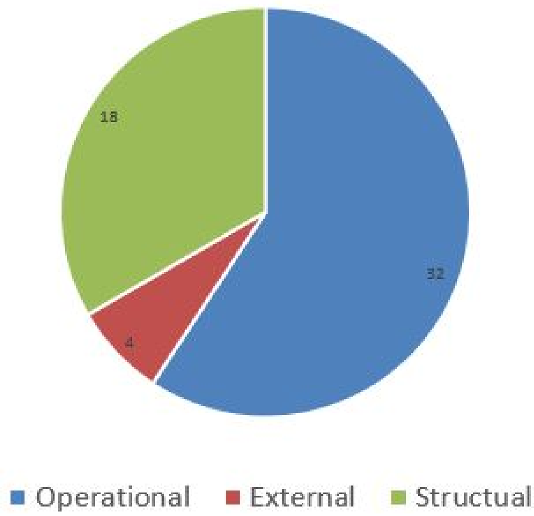

Figure 6.2: Causal factors 2010 - 2016

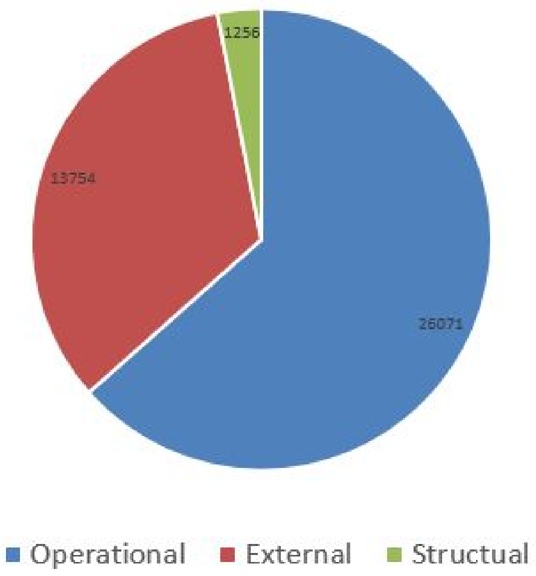

Figure 6.3: Quantity 2016

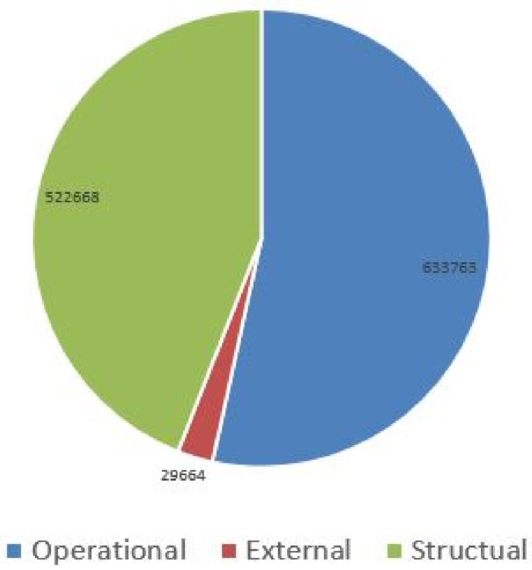

Figure 6.4: Quantity 2010 - 2016

Operational causes imply that the configuration of fish escape originates from human mistakes in installations or during operations. Structural failure is characterised as loss of integrity resulting from structural deficiencies, abrasion or damage. Loss of integrity are characterised by when the system can not maintain its ability to keep fish enclosed. Furthermore, external causes are characterised as unpredictable stimuli from elements outside of the system which conflicts with the farm. In 2016, 65 % of the damages to the system occurred in an operational context, whereas 16 % and 19 % resulted from structural and external causes respectively. From 2010 to 2016, 59 % of the causes were operational, 33 % and 8 % were structural and external.

In terms of quantity escaped in 2016, 63 %, 34 %, and 3 % were operational, external and structural respectively. From these, 92.36 % escaped from holes in the net, 7.15 % from submerged nets and 0.48 % during direct fish handling or treatment. This indicates that fish farms have experienced structural issues frequently in 2016, but a minimum of these resulted in large escapes. However, the opposite was observed in escapees caused by external elements such as flotsam or predators, which had a far more significant impact. Furthermore, out of 63 events with either submerged or holed nets only did fish escape from 12 of these. An additional 11 events of fish escapes resulted from incorrect handling or technical failure during the counting of lice and delousing. The quantity escaped from these events was significantly lower.

From 2010 to 2016, the number of escapees resulted from 54 % operational, 44 % structural and 2 % external causes. From these, 82.26 % escaped from holes in the net and 17.73 % from submerged nets. No further configurations of escapes were addressed in this database. This indicates that in the long run, a structural failure that results in fish escape is more severe compared to a failure caused by operational mistakes and external factors. This can be explained by fish escape that is caused during operations that can be intervened in some way by operators if the accident is discovered quickly enough. Swift intervention following a structural failure requires a sophisticated surveillance and emergency system, and is naturally discovered subsequently.

Regarding seasonal influence, fish escape occurs less frequently during summer. Reported escapes from 2010 to 2016 reveals that fish escapes are three to four times more likely to happen during fall and winter as compared to spring and summer. Reports of holes in the net and submerged nets in 2016 are evenly distributed throughout the year but have more severe outcomes during fall and winter. This may be connected to harsher weather with colder temperatures which both affect the environmental impact on the system and the cognitive abilities of on-site workers. In addition, the databases address respective storms as influential factors, which usually occurred from October to January. To provide more accurate answers for seasonal influence on fish escape, an older database that tracks near-accidents and escapes over a long period could be utilised to answer this.

Furthermore, the parameter assessments revealed that most escapes are of significant sizes. During 2010 - 2016, 50 % of the escapes had between 1000 to 9999 units of fish released. 43 % of the escapes are labelled as large escapes, with over 10 000 escaped fish. This indicates that significant amounts of fish escape during these events, further increasing the importance of having mitigating means that can restrict the quantity escapees during accidents. Furthermore, 50 % 20 % and 10 % of the escapes were from pens labelled as large, medium and small. Due to inconsistent reports, 20 % of the pens are of unknown circumference. 41 %, 22 % and 15 % of escapees happened from pens labelled as shallow, medium and deep. 22 % of these remain unaddressed.

6.1.1 Estimated Frequencies of Fish Escape

Quantification of different configurations for fish escape enables one to review the frequency of respective types of fish escapes. The numbers can be used to propose where to implement risk-reducing measures wherever necessary. Table 5.3.8, 5.3.9 and 5.3.10 displays the obtained frequencies for each configuration of fish escape.

By using a risk acceptance criteria of 10^{-4} the findings indicate a tolerable annual occurrence rate for holes in the net throughout Norway. Predators, cleaning and handling of the net, wear and tear from weights, ropes and dead fish systems are among the most frequently reported causes of holes in the net. Deviations of procedures are the strongest underlying factor for these failures, especially during the mounting phase.

However, the estimations have some weaknesses, especially when operational intervals are accounted for in the calculations. These intervals were made by the use of available information and correspondences with Langøylaks AS, and should not be considered applicable for each fish farm in Norway. This is due to the different strategies used by each respective company. For instance, the intervals for cleaning of the net differs from companies that use impregnated nets or not. Additional issues with the estimations are potentially invalid observations, especially regarding flushing of the net. Here it was difficult to distinguish between events where holes in the net have been caused or discovered during the washing operation. Consequently, there could be some discrepancies in the calculations given that the assumptions are invalid or the misinterpretations were implemented in the database.

6.2 Bayesian Belief Networks

The analyses of the databases have provided insight and data to structure a holistic network of factors associated with fish escape. The estimations from the databases have been implemented in the networks to quantify the frequencies of different risk influential factors. The following sections present one qualitative and two quantitative networks in which includes a variety of factors contributing to fish escape. The network is constructed to review how different subgroups affect each other, and through a sensitivity and strength of influence analysis of which factors have the largest impact.

6.2.1 Quantitative Network for Fish Escape

Figure 6.5 displays a network designed to map the influential factors for fish escape. Variables in this network are based on the factors found in the database. Preliminary assessment for this database can be read in Section 4.2.1. Fish escape results from a hole in the net and submersion of the net in this network.

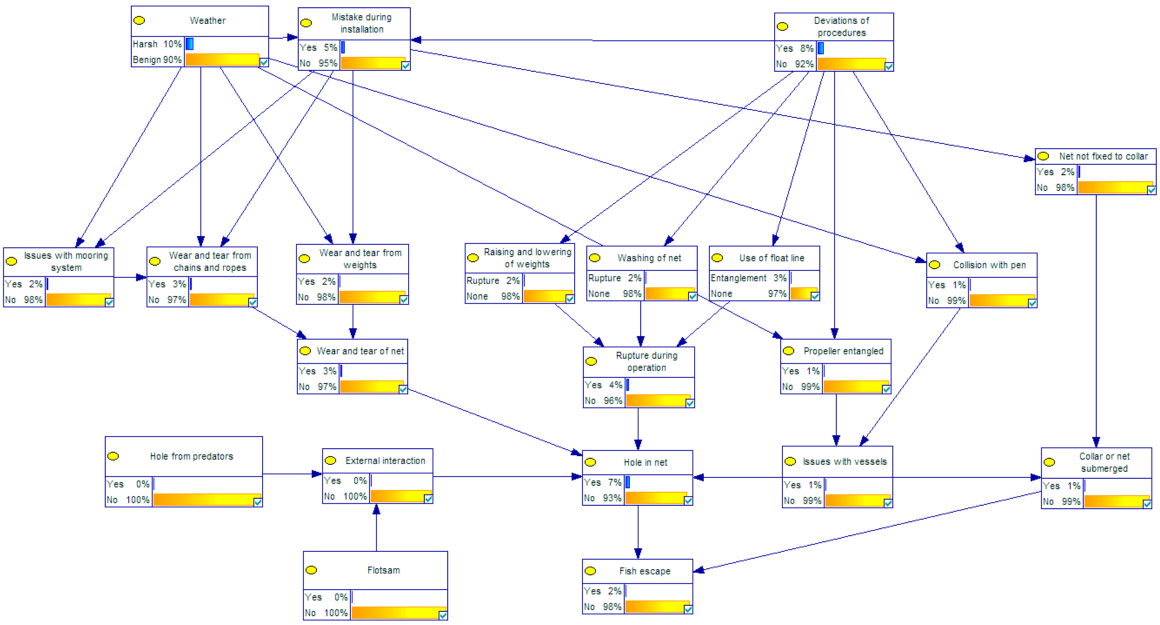

Figure 6.5: Bayesian Belief Network for fish escape

The database is heavily focused on man and technology aspects of fish escape, as organisational influence is difficult to capture in the fish escape reports. Thus, every node addresses contributing factors in a man and technological manner, with exception to the node 'Deviations of procedures'. This node was implemented to ensure that organisational aspects were somehow addressed in this network. This particular node is addressed in Figure 6.10 in the upcoming Section 6.2.3.

This network is quite large with several variables which makes assignment of the conditional probability tables a challenging task. The use of obtained frequencies is not directly applicable for this network, as the node of interest usually is assigned a parent node. The database did only give a basic indication of the frequency for the different states, and not the final frequency given an earlier event has happened which is the basis of Bayes' theorem. To obtain these values correctly is an impossible task. Thus, the descendant nodes being subject to the state of the parents' node made it difficult to use the findings in the database. However, it did give an indication of the values which can further be either increased or decreased if the parent node has a positive or negative influence. Given the output from this network is not representative, it was chosen to create an additional network that was narrowed down to enable the use of the obtained frequencies.

Figure 6.6 displays the simplified network for fish escape. Hole in the net was chosen as the only variable causing fish escape, as the quantity of data from submerged net events was insufficient to provide a basis for estimations. The setup and conditional probability tables were created and assigned using a pessimistic approach under supervision from a PhD Candidate at NTNU.

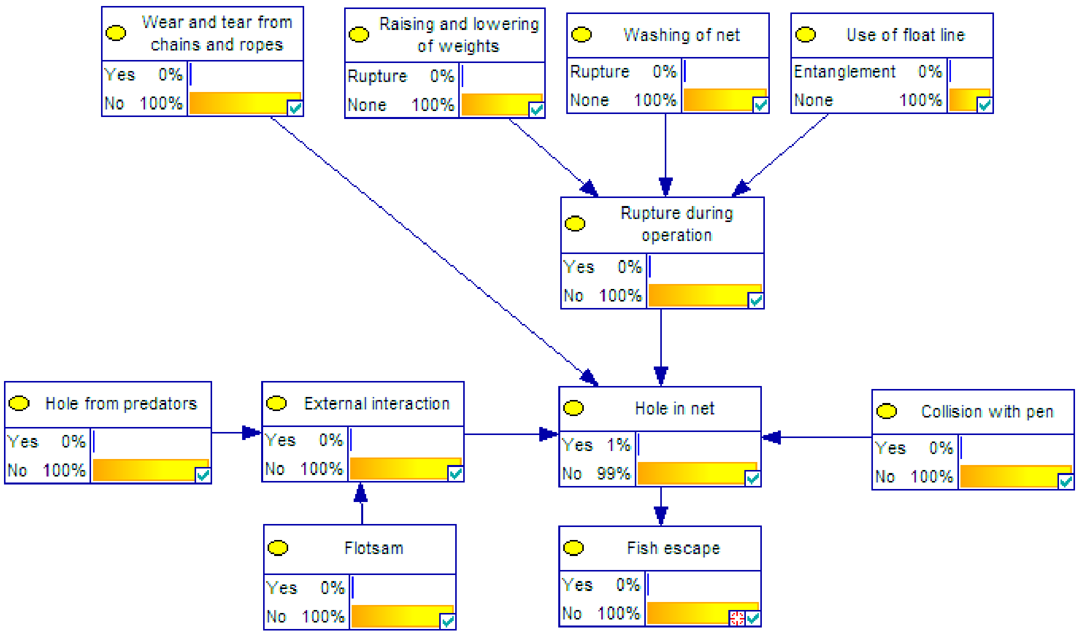

Figure 6.6: Simplified network for fish escape

Furthermore, the network consists of four subgroups which independently contribute to holes in the net. The subgroups are divided within rupture during operations, influence from structural abrasion, external factors, and vessels. To review how the variables affect the final node, a sensitivity analysis was conducted. Figure 6.7 and 6.8 displays the sensitivity analysis and strength of influence. Sensitivity analysis colourises parameters which are important for the calculation of the posterior probability of the final node.

White and grey nodes are interpreted as passive, i.e. it do not affect the final posterior probability distribution of the targeted node. The colour red implies that a change of the node properties can have a large impact upon the final event. Strength of influence are illustrated by thickened arcs, where thicker arcs indicate stronger influence. Figure 6.1 displays the distribution of the final node.

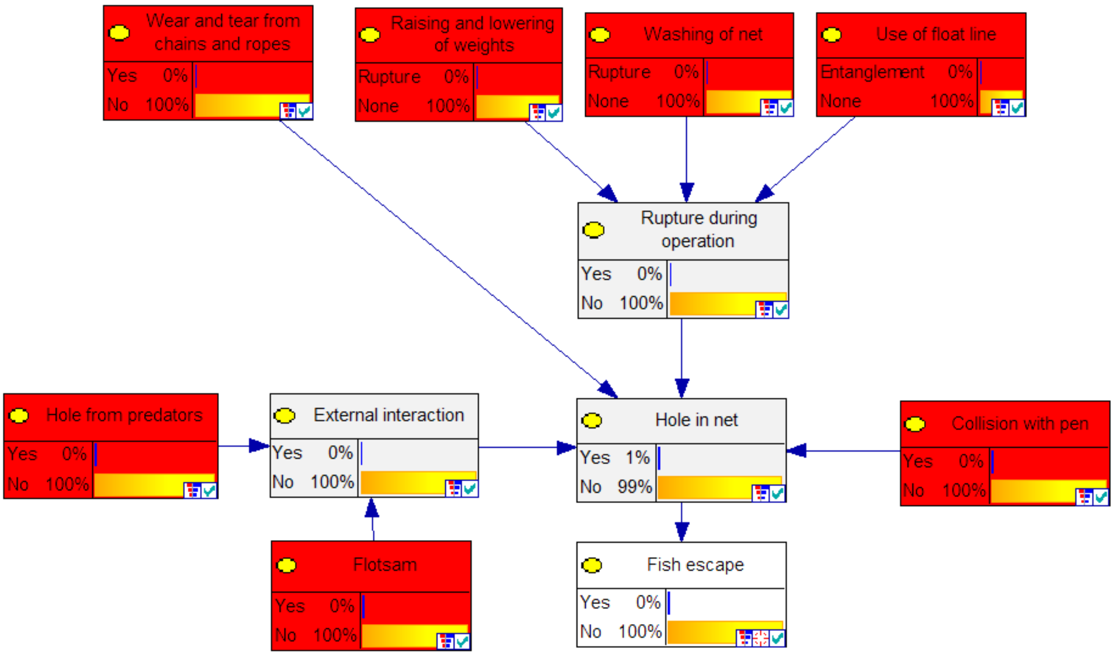

Figure 6.7: Sensitivity analysis for fish escape

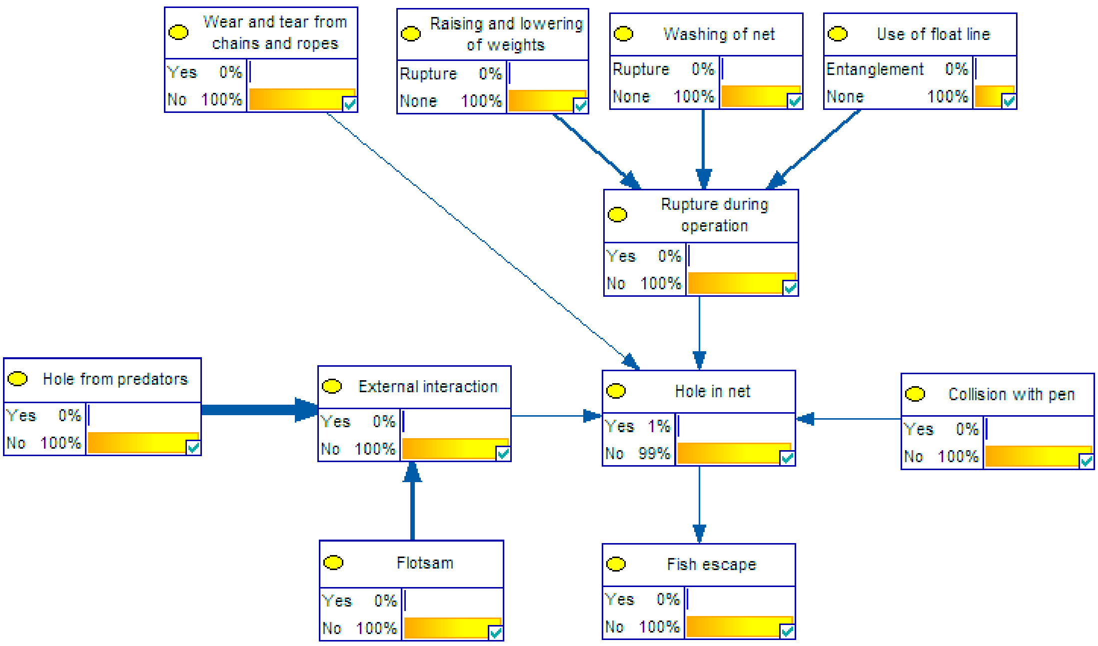

Figure 6.8: Strength of influence

Table 6.1: Frequency of fish escape, Norway

Fish escape	
Yes	0.0010624252
No	0.99893757

The node 'Fish escape' is strongly affected by every node in the outskirts of the network, with strong influence from predators and rupture during operations. The strength of influence reflects the findings in the database, where predators and accidents during operations are highly represented. Given the variables put into consideration, the results determined a 0.001 % annual probability of fish escape in Norway as a result of holes in the net. The probability of holes in the net are 0.006 %. Note that this result are the product of the chosen variables put into context, and is perhaps too inadequate to provide any clear answers around its realistically.

6.2.2 Qualitative Network to Review Organisational Influence

Figure 6.9 displays a qualitative network based on a variety of factors contributing to the escape of fish. In this network, the rupture of the net is chosen as a hazardous event as it accounts for 82.26 % of the total escapees from 2010 to 2016.

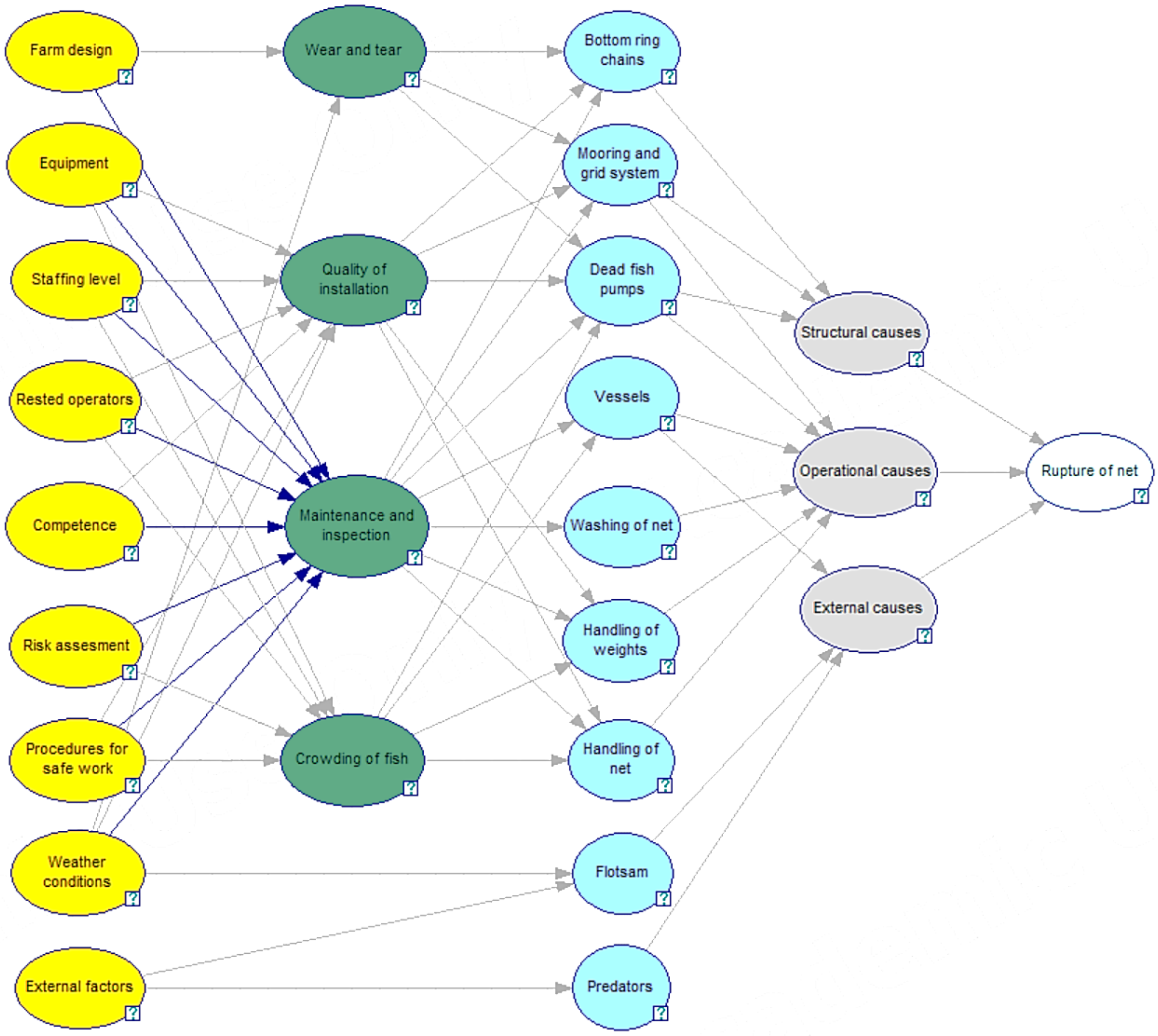

Figure 6.9: Qualitative Bayesian Belief Network - Rupture of Net

The network is divided into several parts, built upon the setup from Figure 2.3 in Section 2.4.3. The yellow nodes represent organisational risk factors, which can be interpreted by indicators. The green nodes illustrate operational and technical factors, and blue nodes display associated components. The grey nodes categorise which failure context the prior nodes leads to. This network has a dual function, it can either be a purely illustrative mapping tool of factors or be used to review organisational influence. This can be done by converting the organisational factors to bar charts with assigned values from operators or the management to review if the organisational impact is negative or positive. Table 6.2, 6.3 and 6.4 are simple examples of organisational indicators that can be implemented and measured.

Table 6.2: Organisational risk indicators for (a) farm design, (b) equipment and (c) staffing

(a)

Farm design	Assigned values
Design life left	
Incidents resulted from design defects	

(b)

Equipment	Assigned values
Incidents where equipment are missing	
State of equipment	

(c)

Staffing level	Assigned values
Frequency of understaffing	
Frequency of hiring staff	

Table 6.3: Organisational risk indicators for (d) rested operators, (e) competence and (c) risk assessments

(d)

Rested operators	Assigned values
Working hours exceeded	
Frequency of continuing work exhausted	

(e)

Competence	Assigned values
Competence to execute tasks safely	
Competence to handle dangerous situations	

(f)

Risk assessment	Assigned values
Involvement of employees in assessments	
Quality of risk assessments	

Table 6.4: Organisational risk indicators for (g) procedures for safe work, (h) weather conditions and (i) external factors

(g)

Procedures for safe work	Assigned values
Procedures are applicable to the actual practices	
Procedures are created with input from operators	

(h)

Weather conditions	Assigned values
Incidents where weather affects the system	
Level of flotsam in the area	

(i)

External factors	Assigned values
Level of traffic in the area	
Level of predators	

By selecting relevant factors and determining their state, one has a good basis to create a network to determine the organisational safety status. Appropriate intervals and values for each risk indicator should be chosen and assigned by the management. OSC can be applied to this context to identify indicators which assesses compliance towards internal and external requirements. Fish farmers are expected to have control over a set of indicators, for instance, connected to quality and frequentness of training, inspections, risk evaluations, and near-accidents but missing information can be acquired through use of OSC.

6.2.3 Quantitative Network to Review Organisational Influence

By extracting one of the organisational nodes in Figure 6.9 this section aims to illustrate how Bayesian networks can be applied by fish farmers to review the organisational status. The node 'Procedures for safe work' have in this case been chosen and expanded for further investigations. Figure 6.10 is an experimental quantitative network to determine how organisational factors can lead to deviations of procedures. It also illustrates the strength of influence from the different variables. This network is based on the questionnaires conducted by Thorvaldsen et al. (2016) and Kongsvik et al. (2018). The preliminary assessment and input values can be viewed in Table 4.2, Section 4.2.2.

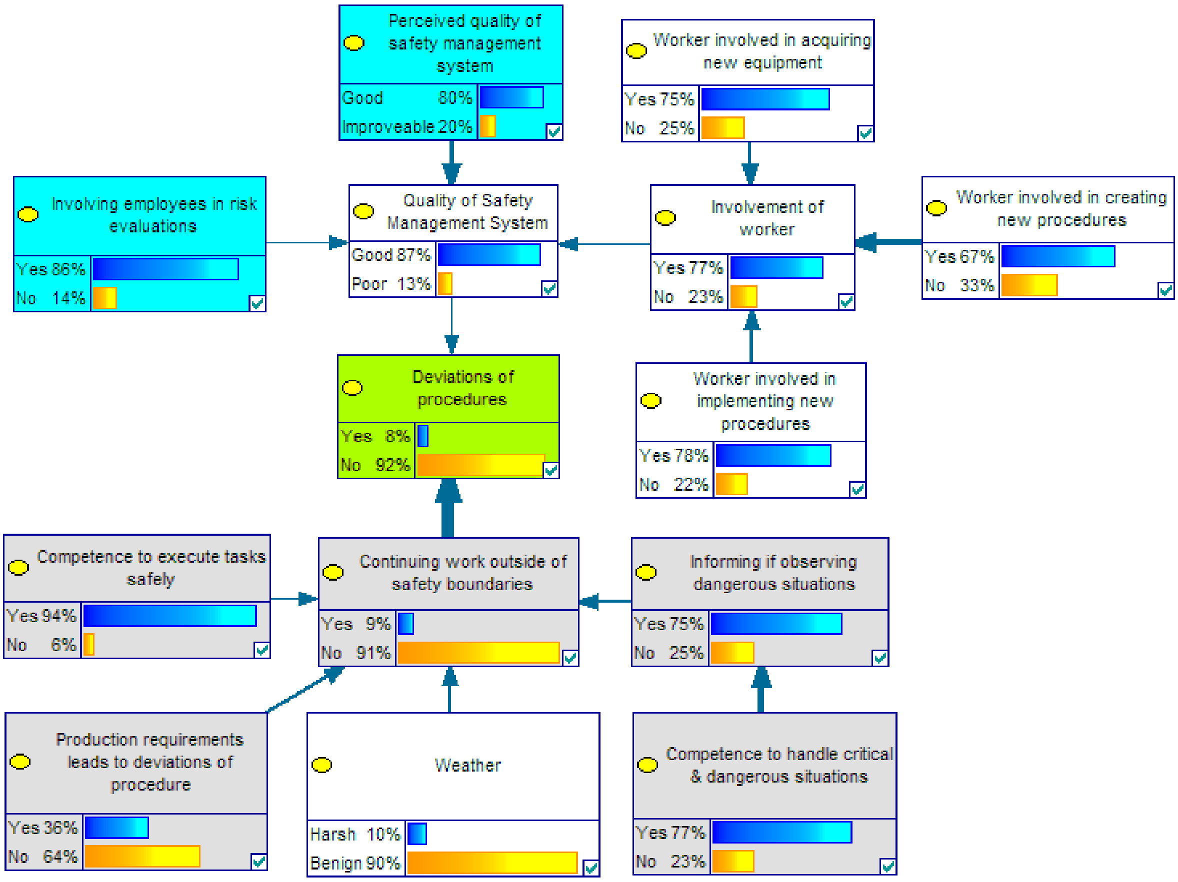

Figure 6.10: Organisational strength of influences

An encountered challenge when creating this network is to assign the conditional dependency values between each linked node. These values are highly subjective and not followingly precisely representative. A more representative network with appropriate input values can be created with input from fish farm management and operators. However, the value of this network comes from the sensitivity and strength of influence analyses which determines which variables have the largest impact. This is done by assigning one node as the target, in this case, 'Deviations of procedures' are the target. Figure 6.11 displays the sensitivity analysis.

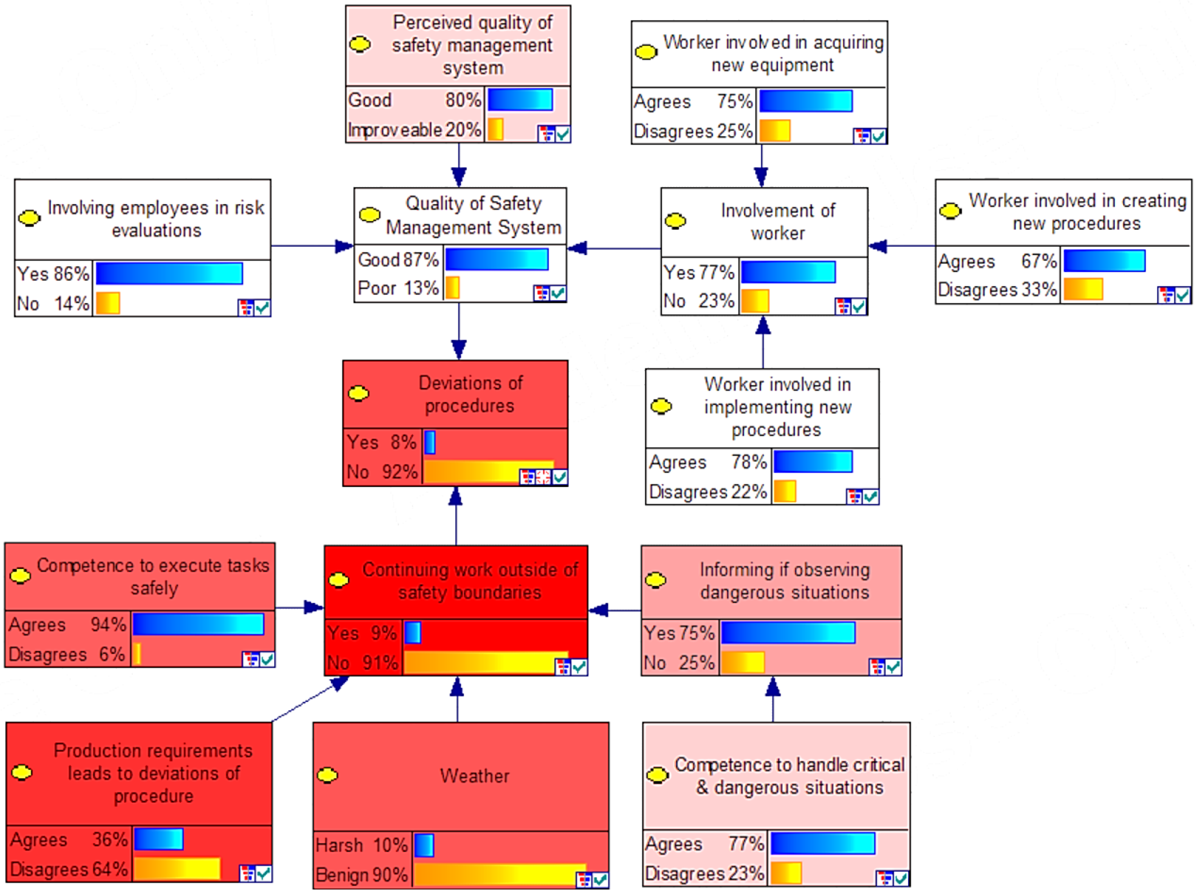

Figure 6.11: Sensitivity analysis of organisational influences

The strength of influence and sensitivity analysis indicates that continuing work outside of safety boundaries is the strongest contributing factor to deviations of procedures. This variable is the descendant of five variables, in which weather, competence to execute tasks safely and deviations of procedures as a result of production requirements has the strongest influence. Measures to enhance the quality of the safety management system have less impact on this network. Thus, this network puts the development of safety culture among the employees to maintain safe work processes at a high priority. Keep in mind that the assigned conditional probability tables are subjective and are a potential error variable in this network. Representative results can be achieved by having the conditional probabilities filled out by competent personnel who understand the principles and method this network is built upon. This method may then be tailored to each respective plant and used to review the current influential factors compromising safe operations. The organisational risk indicators displayed in Table 6.2, 6.3 and 6.4 can be used as a basis for creating a new network for each organisational factor.

7 Discussion

7.1 Data Foundation

Scientific reports require a reliable data foundation, thus it is essential to evaluate the validity of the information this thesis is substantiated upon. Two databases were in this thesis utilised to illustrate how fish can escape, in which the first was based on 114 reports from 2016 submitted to the Directorate of Fisheries. These reports have been narrowed down to 74 events that fit this thesis' defined scope. The second database for 2010 - 2016 was narrowed down to 54 events. The following sections discuss the studied reports and databases.

7.1.1 Reports from the Directorate of Fisheries

Overall, the reports were well written and presented sufficient information about escapes and suspected escapees. The impression is that the current reporting system of fish escape is good, which is further confirmed by the survey conducted by Kongsvik et al. (2018). The survey indicates that 94 % of the participants agreed that the reporting system is good. However, 67 % have experienced report-worthy nonconformity that was not reported. The new online solution for reporting fish escape which was introduced 1. February 2019 might reduce this. Online reporting systems aim to enable swift and consistent reporting, with the opportunity to use predefined information about the locality. Thus, the operators can worry less about the formalities in the report, i.e. filling out plant details, and focus on the circumstances of the accident. Furthermore, an online system can systematically archive information more efficiently, in which analytical approaches can be applied to obtain statistical properties of the industry. This can be viewed as incremental progress towards using the information to ensure safe cultivation of salmon in the future.

The reports received from the Directorate of Fisheries is a valuable resource to investigate and understand the phenomena of fish escape. However, challenges were encountered during the construction of the first database. Improper and inconsistent reports introduced difficulties in the categorisation process, often caused by lack of information. These reports are standardised with a clear interface easy to fill out. Despite this, several reports were left with sections blank which left the reader with no information on important parameters such as type of farm, which kind of species they are cultivating and the number of escapees. Furthermore, the reporter is supposed to fill out a checklist which roughly indicates the cause of escape supported by a separate written specification. Either was in certain reports left blank or with anticipations, leaving the reader to make up their own assumptions about the cause.

Part 1 is often filed immediately after an accident. Consequently, Part 1 does not always cover the incident sufficiently, but the reporter has the opportunity to inform more thoroughly in the secondary report. However, an observed tendency was that Part 2 was often left blank and uncorrected for discrepancies, and not submitted in certain cases. This created difficulties in estimating the total number of escapees and which measures the company implemented to prevent such accident to happen again.

7.1.2 Database

The databases this thesis is built on is unarguably an important asset for fish farm companies to prevent future escapes. The insight of different configurations for how integrity can be compromised and followed by fish escape enables one to allocate preventive and mitigating efforts where it has the most impact. The two databases, where the first consists of both escapes and suspected escapes and the latter only escapes, have provided a good basis for reviewing the issues contributing to fish escape. 2016 was a copious year with numerous reports issued to the Directorate of Fisheries, providing a large range of causes that led or could have led to fish escape.

However, the database is purely limited by the quantity and quality of the reports. The database is a direct interpretation of the issued reports. Thus, it relies on the information submitted by aquaculture companies to create a comprehensive interpretation in the database for the users to understand. Section 7.1.1 discusses the lack of information in the reports which is the main cause of inconsistency in the database.

The parameter assessment in which tendencies were explored could be utilised to a greater extent by introducing additional parameters associated with the net, mooring system and collar. In the reports, the component supplier and age are displayed. Therefore, it could be interesting to study the age and material properties of the net exposed to abrasion or predator holes.

7.2 Cause of Escapes

Escapees result from a variety of influential factors associated with abrasion, operations and farming equipment. The analyses of the database show that the dominant cause of fish escapes is holes in the net caused in an operational context. However, in terms of severity, the findings indicate two different answers. In 2016, escapes resulted from external causes had the most severe impact in terms of quantity escaped. Structural failure had considerably low amounts of escaped fish per event this particular year. The opposite is found for the period 2010 to 2016, where structural failure had the most severe consequences as opposed to external factors. This implies that the distribution of events in 2016 does not coincide with the previous years. Escapes caused during operations remain approximately alike in regard to the number of events during 2016 and the earlier years but has in general lower amount of escaped fish per event during the six-year period. Consequently, the long term data can conclude that escapes resulting from structural causes are far more severe compared to escaped caused by external and operational causes.

In 2016 there were 12 small escapes, with additional four registered events with single escapees which in total accounted for 1 % of the quantity escaped. Six medium sized escapes accounted for 73 %, and one large escape accounted for 26 % of the total quantity. The largest escape was caused by a collision from an external vessel, which caused 10 766 fish to escape. Hence, the distribution of quantity escaped is heavily occupied by external causes. The medium-sized escapes resulted from a variety of causes, among these were an additional collision with a vessel, abrasion from bottom ring chains, ropes, weights, and the dead fish system. In addition, two events with handling of the net and weights caused between 1000 and 9999 fish to escape.

The smaller escapes were usually caused by loss of fish during physical handling or treatment. Eight events did occur from wrongful translation of the fish, where fish accidentally was released from misplaced chutes with no secondary safety nets to prevent this outcome. Two events resulted from flooded tanks which fish were temporarily stored in. These events resulted from a mix of technical failures and deviations of procedures. Furthermore, five small sized events were caused by a hole in the net where the majority of the holes resulted from wrongful translation of the dead fish system causing the equipment to rupture the net. In addition, one event involved the use of float lines to crowd fish prior to delousing. It is however unclear what led to the hole, it could be the floaters' rough surface or entanglement. The last small event was an escape following structural abrasion from a weight which caused a hole. It is more difficult to determine the extent of small escapes until the production process has reached its finalising phase and detailed counting of fish can start at the slaughterhouse. Therefore, the numbers issued to the Directorate of Fisheries, which usually is based on the number of re-catches, can potentially be lower than the total amount of escapees.

Furthermore, the database from 2016 indicates that holes in the net and submersion of the net do not necessarily lead to fish escape. In fact, in 2016 there were only seven notable and 12 minor events from in total 74 events. That implies 69 % of the reported events did not result in an escape. The explanation for why these events usually did not result in an escape can be complex and has several answers, but remains mostly unaddressed in the reports. The majority of the events were caused by operational mistakes and could be de-escalated by quick intervention from the operators. The operators have the opportunity to block holes by the use of hand nets if it is within reach or simply tightening up the hole before it is sewed up. Other factors that should be taken into consideration are the area where fish thrive. If the hole is located in an area where fish rarely swims, the risk of escapes is considerably lower. Nevertheless, companies are obliged to report any occurrences of holes in the net even it is not of significant size. Several reports do not include the size of the hole. Hence, the database might consist of several episodes where the holes are too small for fish to escape through. Still, this is useful information for as the goal this thesis is to investigate how integrity can be lost.

The database for 2010 to 2016 consists solely of fish escape based events as opposed to the database for 2016. This database is more representative for determining the context and consequences of different types of escapes. From 2010 to 2016 there were 4 small, 27 medium and 23 large escapes which are 4 %, 50 % and 43 % of the total number of escapes. There is observed no correspondence between specific causes of fish escape and the amount escaped in the database. The causes for fish escape are distributed randomly when attempting to sorting the quantity of escape from small to large.

Regarding the parameter assessment, it is difficult to determine the influence of these parameters as no further information about the circumstances are provided. The short answer is that farms that are shallow and large in circumference have a higher escape rate. These findings are substantiated from both databases. These parameters could be assessed in a better manner if further parameters such as relative water depth and environmental conditions are included. The answers can provide insight into how topography and exposure affect the physical configuration of the fish farms.

With both databases in consideration, the most frequent cause for fish escape is handling of weights. It did contribute to 21.31 % and 21.10 % of the total escapes in 2016 and during 2010 - 2016 in terms of quantity. Handling of weights is associated with operations such as net change, delousing and harvesting which require raising and lowering of the bottom rings in which weights are attached. In addition, weights are mounted to diverse components in the mooring and grid system. Winches and cranes are usually used to re-position weights, which introduces large forces in motion. The database singles out deviation of procedures, inaccurate operator manuals and haste as underlying factors. The following causes that are highly represented are abrasion from bottom ring chains which accounted for 13.91 % of the escaped fish during 2010 - 2016. During 2016 this had a lower impact upon fish escape, with only 3 % of the escaped quantity as a result of this cause. Furthermore, issues with dead fish pumps occurred frequently in both databases. In 2016, it accounted for 14.09 % of the escaped fish, and 9.22 % during 2010 - 2016.

Single events in the database for 2016 are observed to have a major impact on the distribution of causal factors for fish escape. This is due to a small data foundation for comparisons, with only 23 fish escapes. Thus, specific causes that are rare but encountered this year can have a large impact on the causal distribution. For instance, one accident during handling of the net led to a hole in the net which accounted for 20.54 % of the entire quantity escaped in 2016. During 2010 - 2016, handling of the net accounted for only 1.53 % of the escaped quantity. Consequently, the database for 2016 is not representative to use for determining quantity escaped associated to specific causes. It should rather be used to investigate the frequency of how the fish farm is damaged.

The estimated frequencies are subject to the findings from both databases, but mainly from 2016. This year was eventful, which provided information about different causes for suspected and actual fish escapes. Despite the number of events with escapes were low, it gave input in how the fish farm can lose the ability to keep fish enclosed. The most frequent issue encountered is the dead fish system, in which abrasion and incorrect handling caused holes. There are registered more events addressing issues associated with the cleaning of the net, but due to insufficient information in the reports, it is hard to distinguish between the discovery of holes during cleaning and holes as a result of cleaning. Furthermore, holes caused by predators occurred frequently in 2016 but have only led to one large escape during the six years.

It is not expedient to attempt to capture a representative frequency for each configuration of fish escape and apply these to all plastic fish farms. There are too many variables in each fish farm to put into consideration. For instance, the strategies for work processes has revealed to be one of the strongest factors in causing and avoiding fish escape. Strategies for work operations differ from company to company, so this influential factor should be assessed individually for each fish farm. Furthermore, there are some similarities that can provide grounds for comparisons. Fish farms are usually composed of the same components verified by accreditation bureaus. This allows for using estimations in terms of structural failure if the database is constructed in a manner that groups events in terms of similar layout, components used and dimensions. The reports issued to the Directorate of Fisheries do capture the dimensions, supplier and purchase date of the collar, net, and the mooring system. These variables are not addressed in this thesis but could be interesting to investigate.

7.3 The Operative Model for Fish Escape

The final model is a simplified version of the first network created. Simplification of the prior model was necessary, as the extensive model included every registered configuration of fish escape. This led to a number of nodes difficult to restrict. Each node introduced and connected to another node increased the amount row and columns of the conditional probability tables for that node exponentially. The large tables decreased the usability of the obtained frequencies as there are too many variables that were merged. Therefore, it was more appropriate to design a secondary, simplified model which only includes the most important risk influencing factors. The simplified model is less informative than it's counterpart but enabled use of the estimated frequencies for accidents.

The output from the final operative model indicates an annual 0.001 % probability for fish escape in Norway based on the information from 2016 and the period 2010 to 2016. The model is restricted to be only affected by external factors such as predator and flotsam, structural abrasion from ropes and chains and rupture of the net from a set of operations and collision with vessels. The strength of influence analysis indicate that predators and rupture of the net from certain operations has the largest impact upon creating holes in the net.

Use of Bayesian Belief Networks to assess the risk of fish escape has been an insightful way of understanding the contributing and underlying factors for these incidents. The software is graphical and flexible regarding implementing or removing nodes and are in general a useful tool. Further modifications in the model can be implemented by assigning the states to determine the size of fish escapes as a result of a variety of operations. For instance, it can determine whether or not escapees caused by structural failure has more severe consequences than escapes resulted from inaccurate handling of weights.

7.4 Model to Review Organisational Influence

The network which reviewed organisational influence is able to both have a quantitative or qualitative approach depending on the purpose. The qualitative approach is useful for addressing influential factors and to design a holistic network of causes, which can contribute to a better understanding of the factors which lead to fish escape. The relatedness between a wrongful installed weight and the organisational conditions is not self-evident but can be better addressed through a qualitative network. The method of using Bayesian networks to address the influences is flexible, as nodes can easily be added or removed. This allows for adjusting the network to include the range of equipment, workers, and procedures involved.

Qualitative networks are usually allowed to be larger and more complex, as it does not require any assignments of CPTs'. However, quantitative networks require assigned conditional dependencies to achieve any useful output. For these networks, it is important to balance the complexity and simplicity as complex networks can be extremely time-consuming and difficult to master whereas a simple model may fail to capture all the matters of relevance. Hence, it is recommended to initially apply the quantitative approach on smaller networks consisting of one subgroup. These networks can be useful on its own or can be inserted into a larger context if desired.

The examples in Section 5.2.2 and 5.2.3 illustrate how networks can be used as a tool in risk assessments to review organisational influence in an industrial context. This network can measure and illustrate the change in risk following a change in the organisational condition through sensitivity or strength of influence analysis. This network is great to use in conjunction with OSC, which can be used to identify indicators and to audit the organisational conditions. The initial parts of OSC address the cause for a problem, the operations or practices it is connected to and which organisational condition important for these tasks. This process is time-consuming and requires the involvement of employees from every level to collect sufficient information, but produces very useful findings. These findings can be directly be used to construct the layout of the network. The further steps in OSC are to derive checkpoints for each requirement and to see how the company meets the requirements. The findings can be implemented in the network to address and determine the organisational practices and compliance towards the authorities regulations, which can be used as a basis to develop necessary changes.

The experimental network determining the influential factors leading to deviations of procedures during work operations seemed to be useful for identifying areas of improvement. Given the input values from the questionnaires and a subjective assignment of the conditional probability tables, the network identified production requirements as a large contributing factor for deviated procedures. Furthermore, the organisational networks can be further implemented in the operative network to review the impact the organisation has directly on causes for fish escape. This was done by implementing the node 'Deviations of procedures' in the operative model, which was connected to work operations and mistakes during installation.

8 Conclusion

Escapes results from a variety of influential factors associated with operations, abrasion, and the use of farming equipment. The analyses of the database show that the most frequent cause of fish escapes is holes in the net caused during operations. The most severe escapes are caused by structural failure. This may be explained by the ability to discover the accident and followingly intervene is dependent on the surveillance system or inspections as opposed to accidents occurring during operations. Overall, most reported cause for fish escapes is holes in the net caused by wrongful handling of weights, followed by abrasion from bottom ring chains. However, the reference year of 2016 revealed interesting findings. Fish do not escape in most of the cases where the system has been damaged, in fact, 69 % of the reported events did not result in a fish escape. In addition, other issues than the aforementioned problems were encountered more frequently. Issues with the dead fish system, both from abrasion and translation, in addition to handling and cleaning of the net were far more represented during this period.

The organisational influence was found to have a large impact on the risk of fish escape. Sub-optimal human-technology interface, working conditions and improper risk assessments of the farming system have led to recent fish escapes. The database indicates a strong interconnection between fish escape and the inability to follow established procedures for work operations. Common reasons for this are insufficient risk assessments, training of employees or if they perceive a practical solution to be more efficient than the method developed by the management.

The use of Bayesian Belief Networks to create an operative and organisational model to assess influence has provided some interesting perceptions on how risk can be managed. The operative model is created in a manner that enables an easy understanding of the risk influential factors. The output is however limited by the data foundation and assumptions, and should not be considered representative. The assignment of complex conditional probability tables has been very difficult. Furthermore, the network to map and determine organisational influence could be a feasible tool in combination with OSC. However, it requires good knowledge of the software and the organisation to be fully utilised.

Further Work

Recommendations for further work is to implement the use of Bayesian networks in practice. Networks in general can be a useful tool for fish farming companies to reveal weak links within the company or to review the relative changes in implementing new measures.

In addition, continuous development of the database concerning fish escape is crucial to avoid future escapes. The rapid development of the aquaculture industry will require new solutions to prevent new problems. The new online reporting system is believed to improve the quality and quantity of the database. Further suggestions for the database is to add the operational context the accident happened in, relative water depth and environmental conditions to better utilise parameter assessments.

References

Cardia, F. and Lovatelli, A. (2015). Aquaculture operations in floating hdpe cages.

Directorate of Fisheries (2017). Tiltak mot rømt oppdrettsfisk.

Directorate of Fisheries (2018). Data for Research.

Directorate of Fisheries (2019). Meld rømming elektronisk.

Ellefsen, K. E. S. (2014). Prinsipper for overføring av fisk mellom brønnbåt og oppdrettsmerder.

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., Eguiraun Martinez, H., Watson, W., Stahl, A., Sunde, L., Schellewald, C., Skøien, K., Alver, M., and Berckmans, D. (2017). Precision fish farming: A new framework to improve production in aquaculture. *Biosystems Engineering*.

Hatlem, O. H. and Kvamme, B. W. (2016). Design for operational efficiency and hse in marine operations between floating cage collars and service vessels in the aquaculture industry.

Holen, S., Utne, I., Holmen, I., and Aasjord, H. (2017). Occupational safety in aquaculture – part 1: Injuries in norway. *Marine Policy*.

Hollnagel, E. (2014). Safety-i and safety-ii : The past and future of safety management.

Holmen, I. and Thorvaldsen, T. (2018). Occupational health and safety in norwegian aquaculture: National profile for a fao report on global aquaculture ohs.

Holmen, I., Utne, I. B., and Haugen, S. (2017). Organisational safety indicators in aquaculture – a preliminary study.

Holmen, I. M., Utne, I. B., and Haugen, S. (2018). Risk assessments in the norwegian aquaculture industry: Status and improved practice.(report). *Aquacultural Engineering*, 83.

Høyli, R. (2016). Assessing the risk of escape from marine fish farms.

Iversen, A., Hermansen, Ø., Andreassen, O., Brandvik, R. K., Marthinussen, A., and Nystøyl, R. (2015). Kostnadsdrivere i lakseoppdrett.

Jensen, F. V. (2007). Bayesian networks and decision graphs : February 8, 2007.

Jin, J., Selvik, , Yin, D., Yang, X., Aksnes, V., and Fathi, D. (2018). Review on typical marine operations in aquaculture and numerical simulation of one example operation scenario. *Proceedings of the International Offshore and Polar Engineering Conference*.

Kongsvik, T., Almklov, P., and Fenstad, J. (2010). Organisational safety indicators: Some conceptual considerations and supplementary qualitative approach.

Kongsvik, T., Holmen, I. M., Rasmussen, M., Støkersen, K. V., and Thorvaldsen, T. (2018). Sikkerhetsstyring i fiskeoppdrett. en spørreskjemaundersøkelse blant ledelse og stabspersonell.

Kristiansen, D., Aksnes, V., Su, B., Lader, P., and Bjelland, H. V. (2017). *Environmental Description in the Design of Fish Farms at Exposed Locations.*

Langøylaks AS (2019). Personal conversation with Johannes Møkster.

Marine Harvest (2018). *Salmon Farming Industry Handbook,.*

NMTF (2005). The Norwegian Aquaculture Act. https://www.regjeringen.no/no/dokumenter/the-norwegian-aquaculture-act/id430160/.

NMTF (2011). Technical Requirements to Floating Aquaculture Installations.

NMTF (2014a). Regulation on Construction and Supervision of Small Cargo Ships.

NMTF (2014b). The Regulations on the Operation of Aquaculture Facilities.

Olafsen, T., Winther, U., Olsen, Y., and Skjermo, J. (2012). Value created from productive oceans in 2050.

Rausland, M. and Utne, I. B. (2007). Risikoanalyse - teori og metoder.

Skiftesvik, A., Bjelland, R., Durif, C., Johansen, I., and Browman, H. (2013). Delousing of atlantic salmon (salmo salar) by cultured vs. wild ballan wrasse (labrus bergylta).

Skogdalen, J. E. and Vinnem, J. E. (2011). Quantitative risk analysis offshore—human and organizational factors. *Reliability Engineering System Safety*, 96(4):468 – 479.

Thorvaldsen, T., Holmen, I., and Moe, H. K. (2015). The escape of fish from norwegian fish farms: Causes, risks and the influence of organisational aspect.

Thorvaldsen, T., Holmen, I. M., and Kongsvik, T. (2016). Hms-undersøkelsen i havbruk 2016.

Thorvaldsen, T., Holmen, I. M., and Moe, H. K. (2013). Menneskelige faktorer og rømming fra lakseoppdrettsanlegg Årsaksanalyser med fokus på menneskets rolle. Technical report.

Utne, I., Schjølberg, I., and Holmen, I. (2015). Reducing risk in aquaculture by implementing autonomous systems and integrated operations.

Øien, K. (2001). Risk analyses during operation (the indicator project) : executive summary.

Appendix

Report Template of Escapees, Part I and II

MELDING OM RØMMING **DEL 1**
FIRMA AS - LOKALITET (00001)

Registrert av	ETTERNAVN, FORNAVN (011280)
Registreringstidspunkt	2019-04-02 16:38:09
Referansenummer	1001

Kontaktperson/avsender

Selskap	FIRMA (ORGNR)
Kontaktperson	Etternavn, Fornavn
Epost	post@post.no
Telefonnummer	414 24 344

Informasjon om hendelsen

Hendelsen ble oppdaget	2019-04-01 16:40:00
Hendelsen antas å ha skjedd	2019-04-01 16:40:00
Region	Midt
Kommune	Kommunenavn
Fylke	Fylke
Lokalitet	(00001)

Skadested

Hendelsen skjedde fra	Merd
Plassering av anlegget	Sjø
Anleggstype	Stål
Merdnummer	1
Er det hull i not?	Ja
Størrelse på hullet	10*10cm
Hullets plassering (dybde)	15 meter
Hvordan hendelsen ble oppdaget	Røkter observerte hull på kamera.

Årsak

Beskrivelse av årsaken	Det ble oppdaget et hull på videokamera under foring.

Om fisken

Art	Laks
Antatt antall rømte fisk	0
Vekt (gram)	1500

Om rensefisken

Er det satt ut rensefisk der hendelsen skjedde	Nei

Gjenfangst og restbeholdning

Tiltak for å sikre restbeholdningen	Hullet ble deretter bøtt/sydd av dykker.
Er gjenfangsfisket iverksatt	Ja
Beskrivelse av gjenfangstfisket	Det ble satt ut gjenfangsgarn ved denne og ved nabolokaliteten.

Mattrygghet

Er fisken i tilbakeholdstid	Nei
Mattryggheten vurdert av fiskehelsepersonell	Nei

Fiskehelse

Er det påvist eller mistanke om sykdom	Nei

Kommentarer

Ingen fisk observert rømt på video.

Vedlegg

- bilde av hull.jpeg

MELDING OM RØMMING **DEL 2**
FIRMA - LOKALITET (00001)

Registrert av	ETTERNAVN, FORNAVN (011280)
Registreringstidspunkt	2019-04-02 16:38:09
Referansenummer	1001

Kontaktperson/avsender

Selskap	FIRMA (ORGNR)
Kontaktperson	Etternavn, Fornavn
Epost	post@post.no
Telefonnummer	414 24 344

Informasjon om hendelsen

Region	Midt
Kommune	Kommunenavn
Fylke	Fylke
Lokalitet	(00001)

Antall rømte fisk etter omfanget er avklart

Oppdrettsart (meldt i del 1)	Laks
Antall etter avklaring	1
Vekt etter avklaring (g)	1500

Eventuelle korreksjoner ift. DEL 1

Hvilke tiltak er satt i verk for å hindre gjentakelse

Videoovervåkning brukes

Gjenfangst

Selskapets gjenfangst	0
Gjenfangst innleide fartøy	0
Gjenfangst registrert i mottak opprettet av selskapet	0
Gjenfangst i vassdrag	0
Sum gjenfangst	0

Kommentarer

Vedlegg

Ingen vedlegg

NTNU
Norwegian University of
Science and Technology