Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2017
June 25-30, 2017, Trondheim, Norway

OMAE2017-62023

DEVELOPMENT OF A SIMULATOR TRAINING PLATFORM FOR FISH FARM OPERATIONS

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ABSTRACT

The Norwegian aquaculture industry is accident prone compared to other industries and employees report a high number of near-accidents. Furthermore, escape of fish is a challenge for the industry. There is a potential for increased safety for both humans and fish if operators can practice operations in a safe environment. Existing simulators are not suited for this context.

This paper presents results from a research and development project aimed at developing a realistic simulator-based training platform for demanding fish farm operations. Three objectives guided the development process. First, a description of operations, aimed at identifying challenges and training needs, which formed the basis for selecting training scenarios well suited for aquaculture. Second, the development of mathematical models that could be used in the simulator were developed, and finally, a curriculum for training course modules to complete the platform. Platform thus points to the integration of the simulator and the practical and theoretical education of operators. In this article, the first and second part of the process are presented and discussed.

Keywords: aquaculture, fish farming, fish welfare, mathematical models, safety, simulator training.

INTRODUCTION

Towards 2050, a 69 % increase in global food production is required due to a growing population, and it is estimated that food farmed in the oceans will be the major contributor to this [1]. The Norwegian aquaculture production has the potential to increase fivefold during the next 35 years [2]. To be able to grow in a sustainable manner, with respect to both fish welfare and environmental issues, the fish farming industry aims to expand the production to sites more exposed to waves and wind. The technology is gradually developed to meet the increased operational challenges due to heavier weather and sea conditions [3]. The safety of operators on fish farms and vessels is critical in this picture. Production in more exposed areas is likely to involve safety challenges related to extreme weather and shorter availability windows for performing operations. A typical Norwegian fish farm can be seen in Fig.1. Although looking quite harmless on a bright sunny day, the fish farmers reported frequent periods of harsh climate, strong winds and icing on structures during wintertime.

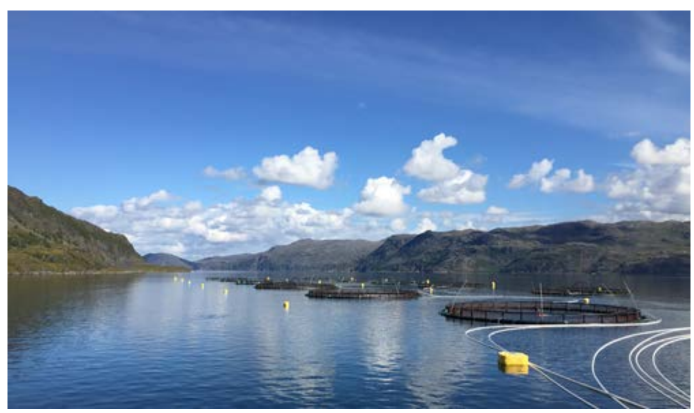

Figure 1: A Norwegian fish farm. The feeding tubes from the barge can be seen in the right lower corner.

Today's fish farms are exposed and physical workplaces, highly influenced by environmental factors. Fish farming is the second most hazardous occupation in Norway after occupational fishing [4, 5]. This is based on the fatal accident rates for the industries, which is calculated as the number of occupational fatalities per 10,000 man-years. The occupational accident

[1] SINTEF Fisheries and Aquaculture was merged into SINTEF Ocean from January 1st, 2017.

statistics for the Norwegian aquaculture industry contains reports of incidents involving hits or blows caused by equipment failure or misactions [6]. A survey answered by 447 workers in the aquaculture industry revealed that during the last two years 76% of the participants had experienced near accidents, defined as incidents that might have caused personal injury [7]. This underlines the need for risk reducing measures to ensure safety for employees at the sharp end.

Furthermore, escape of salmon is a great environmental challenge for the industry. Reported escapes from Norwegian fish farms before 2009 were mainly caused by technological and structural failures [8]. Following the introduction of technological standards for the industry, and the decline of structural failures causing escape of fish, "human errors" were pointed out as a main cause. Recent research proves that the accident causality is often complex and that workers' performance is influenced by both environmental and organisational aspects [9]; e.g. a harsh work environment, demanding work operations, heavy work load, lack of time to perform operations, poor communication, lack of training and consequently variations in worker skills. Preventing escape is also connected to safety for people, as studies have shown that workers may disregard personal safety in order to be responsible workers who keep the fish safe [9, 10].

Previous studies show several challenges documenting the need for improved training of workers in the Norwegian fish farm industry [9, 11]. There is thus a potential for increasing safety for both fish and humans if the operators can test and practice operations, communication and interaction in the safe environment of a simulator. This may increase their understanding and awareness of hazards that will be valuable during real-world operations. Existing simulators, however, are not suited for aquaculture operations.

OBJECTIVE AND SCOPE OF PAPER

This paper presents results from a research and development project aiming to develop a realistic simulator-based training platform for demanding fish farm operations.

Three secondary objectives guided the process:

1. Describe fish farm operations, identify challenges and training needs, and select scenarios for the simulator.
2. Develop mathematical models for a dynamic aquaculture simulator.
3. Develop curriculum for training course modules.

In this context, *platform* is the integration of a technological tool (simulator) with a range of courses for practical and theoretical education of operators. The training platform is based on the aquaculture industry's needs and requirements for a formalised and documented operator training, as well as an in-depth understanding of the operational challenges at the workplace. The simulator will make it possible to rehearse on navigating and mooring vessels within the fish farm, and on performing work at the fish farm. Most important, it will allow training on operations that require interaction between vessels and fish farm structures. Analyses of personal accidents and fish escapes reports show that these operations are associated with high accident risk levels [6, 9].

This paper focus on the process of establishing functional requirements for the fish farm simulator, and summarizes the activities derived from objective 1 and 2.

MARINE OPERATOR TRAINING

Simulators have a long tradition in education and training of air pilots and navigation officers at sea. In Norway, simulator training is widely used by the offshore sector where simulators include vessels, cranes, machine rooms and the interaction between them. An investigation commission following the capsizing of the anchor handling vessel Bourbon Dolphin in 2007, listed simulator training, in particular vessel-specific simulators, as a safety measure for the future [12].

The NORSOK standards developed by the Norwegian petroleum industry define competence requirements for the different activities on the shelf, e.g. crane operations. Crane simulators were implemented for standardized training and certification of operators. This has proved to be effective training, and during the last decade offshore simulators have been established in order to practice anchor handling operations in the offshore fleet. With increasing deep-sea oil drilling activity, subsea lifting operations are becoming highly complex and have to be performed with high precision. These operations can also be exercised in the safe environment of a simulator. The exercises in the simulators are combined with classroom teaching in order to provide a sound theoretical basis. Observation and debriefs are also an important part of the training. In addition to this, simulators are used to train other groups of maritime personnel such as ferry skippers who commonly practice navigation and eco-friendly operation.

Today, the aquaculture sector has few requirements regarding documentation of specific competence or skill. The companies have to comply with the national legislation for landbased industries on work environment, safety management [13]. However, several fish farming companies have internal procedures on specific competence and training that shall be documented. During recent years the governmental bodies have placed a stronger focus on the activities in the industry, and new regulations have been developed. In 2015, the Norwegian Maritime Authority implemented a new regulation for cargo vessels between 8 and 24 meters, thus introducing themselves as a new regulatory authority for the service vessels and workboats in the aquaculture sector. It is expected that formal requirements on navigation training will be introduced in near future. Operator skills and knowledge is critical for the complex marine operations performed in fish farms, and also need to be documented.

For offshore and anchor handling operators, simulator training is seen as an alternative to on-the-job training. The cost of using real equipment, limited access as well as the risk it poses to the crew are given as pros of such training. Furthermore, the closeness to reality is highlighted; simulators may bridge the gap between the real world and the classroom [14].

In simulators, scenarios can be designed to reproduce real incidents, so that crews can learn from previous incidents, including examples of both accidents and near-misses, and find a way to prevent an accident to evolve. This will provide a tool for the workers to practice problem-solving under stress and in interaction with own and other team members. Scenarios can be set up for training situation awareness and decision-making based on available technical and operational information (e.g. trend in monitored parameters) and knowledge within the team. Crew resource management (CRM) is a set of training procedures focusing on the performance of the crew as a team [14], first introduced in aviation simulator training to reduce the negative effect of human error on safety performance. Furthermore, the crewmembers' ability to assess the risk level during an operation can be trained in situations that rarely arise, but might have serious consequences.

The simulator technology has advanced considerably in order to meet the challenges in modelling and visualizing underwater structures in subsea operations, compared to the early navigation simulators [15]. Aquaculture simulators require an even higher degree of complexity, as the training scenarios will include handling and manipulation of flexible structures; net cages, floaters and mooring components. Lifting and tightening operations are performed with cranes and winches operated by crews on board service vessels. Furthermore, the physical models need to reproduce forces by currents, winds and other vessels moored inside the fish farm realistically.

A recent article on simulator training in the maritime industries, states that there are few studies linking the training needs and the real-world demands on operators [16]. Accordingly, this paper aims to describe the development process of creating a simulator for operators in the aquaculture industry, with focus on training needs based on knowledge about everyday demands and work environment challenges for the operators.

METHODS

Methods used in the project are both qualitative and quantitative, and cover the range from personal interviews to mathematical modelling of physical responses. Realistic simulation of marine operations in which vessels interact with underwater fish farm structures requires development of novel simulation technology.

USER REQUIREMENT MAPPING AND SCENARIO IDENTIFICATION

The implementation of the project was based on a user-focused method of systematically gathering and processing data for the development of functional requirements, products and services [17]. This included identification of user requirements and training needs related to operations at the fish farms. The data collection was based on relevant previous studies [6, 8, 9, 18], observations at fish farm locations, workshops and interviews with well boat skippers, service vessel crews and fish farm operators, as well as personnel responsible for recruitment of workers and/or safety management within the companies.

The project aimed to ensure that a range of stakeholders were represented among the informants in order to cover all relevant needs and requirements to a fish farm training simulator. Three workshops and several meetings were conducted with participants found among the partners in the research and development project, consisting of a maritime safety training center, service providers to the aquaculture industry, fish farm companies and a well boat company. Additional informants were selected among companies outside the project.

A selection of scenarios for creating training cases were sketched based on the descriptions of aquaculture operations, challenges and training needs described by the informants and workshop participants. The scenarios were based on the participants' own experiences with demanding operational conditions, near-misses and accidents. Furthermore, a range of topics relevant for classroom teaching were listed. These will be offered as modules together with simulator training cases.

The collection of scenarios is meant to be a starting point for the simulator training platform. More scenarios can be added as fish farm operations change due to technology innovations and improved equipment and procedures, or new challenges arise e.g. due to harsher environmental conditions [3].

MODELLING

Simulation training of aquaculture site operations requires models, which are able to reproduce the topology and dynamics in soft real-time. The physical components of the site are seen in Fig. 2 and consists of 1) anchor lines and mooring frame, 2) floating collar lines, 3) floating collar, 4) mooring buoys, 5) net weight and suspension system, 6) weight cables and 7) net.

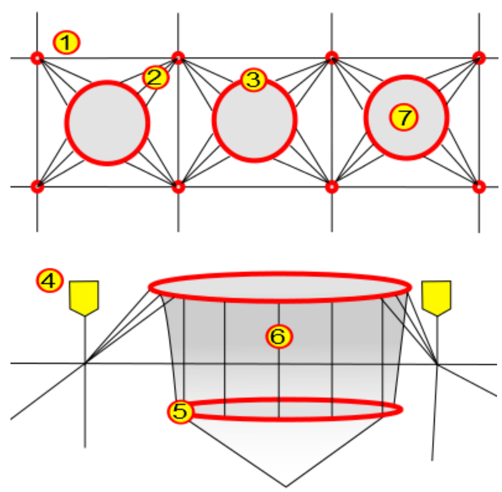

Figure 2: Schematic representation of the main components of an aquaculture structure.

The structure is highly interconnected and consists of smaller, slender and flexible components. The aquaculture site was then constructed in FhSim [19], which is a modular simulation tool which allows coupling of separate models into a "system of systems" model. This initial model was developed in order to investigate the feasibility of constructing an aquaculture site from already available models. Influence from waves and current was represented by the standard FhSim environment implementation which contains current, regular and irregular ocean waves. The environment influence the all structure components through a global interface to the environment model available to all models in the simulation.

Regular cable models defined by endpoint connections were used for wire, cables and lines, while a modal model response model [20] represented the floating collar and the net was represented by a time domain implementation of a finite element model for nets described by Priour [21, 22]. The resulting model in seen in Fig. 3, which reproduce the topology of the site. The reconstructed site topology exhibited poor numeric performance due to the high level of interconnectivity and response of the slender model elements. The numeric issues were encountered predominantly in the connection plates where up to 17 cable models were connected to the connection plates. This was due to cable in maximum tension at the moving the connection plate and inducing larger forces in the other connected cables in the next time step.

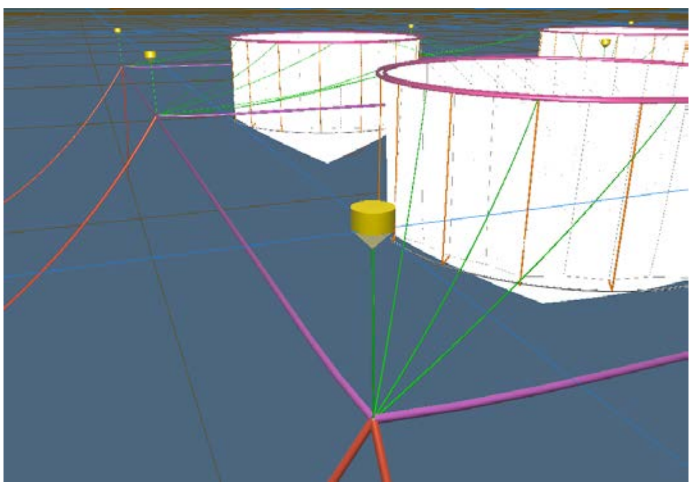

Figure 3: Aquaculture site modelled by separate model components. Cable widths exaggerated for visibility and connection plates are not shown.

The stability of the net model was also sensitive to the time steps required to run the combined model at real-time, which reduced the size of the site the model was able to represent to a single moored net cage.

The numeric stability issues encountered at the cable connection plates implied that better performance could be achieved if the site was collected into a single model which solved the force and movement in the connection points simultaneously. The net was excluded from this model, since several of the identified scenarios involved work on the anchor, weight and mooring system. The implemented model is a continuation and adaption of the underlying simulation technology used to simulate demersal seine ropes in [23].

DEVELOPMENT OF AN AQUACULTURE TRAINING SIMULATOR

In this section, the different steps in developing a training simulator for aquaculture operations are presented. This sums up the findings from the research and development process. The first step was to describe the operations, challenges and training needs, and typical scenarios were selected. Functional requirements for the simulator models were derived from the training needs and scenario descriptions, and these formed the basis for the development of physical models to be implemented in the simulator.

AQUACULTURE OPERATIONS, CHALLENGES AND TRAINING NEEDS

The type of knowledge needed in aquaculture operations may be described as a practical skills and know-how, meaning operators need to know how specific operations should be performed and how specific equipment is used. Many of them also have to manoeuvre different types of vessels. Work is often performed in cooperation with others, meaning good communication is important. Furthermore, they must have knowledge about fish welfare, which today is a mandatory course.

Today, training typically consists of on-the-job training, and many newcomers to the industry get a certificate of apprenticeship through school, which includes two years of practical training at the fish farms. Training of personnel is not standardised, however, and operational procedures may vary between sites and companies. As the industry has grown considerably, the need for formalised training is becoming a relevant topic. The industry prioritise education and competence building among employees, as a means to increase safety for workers and reduce the risk for undesired events. Several companies send their employees to different safety courses, although there are currently no legal obligations for them to do so.

Training must be tailored to meet the challenges of the specific work operations as well as the interaction and communication between them.

The main participants in aquaculture operations are operators who work on the fish farms (fish farmers), operators on service vessels and crew on well boats. The contributions differ between operations. The fish farmers have many tasks, but the main priority is taking care of the fish on a daily basis, meaning feeding, removing dead fish from the net cages and performing inspections to make sure all structures are intact. They must also count lice and perform lice treatments, move the fish between net cages or from the cages and in to the well boats.

Service vessels perform operations on the fish cages and surrounding structures, such as changing the nets and maintenance on the moorings. They also take part in operations such as delousing and moving the fish. Usually specialised service vessels will have crew that are certified divers and therefore can perform visual inspections of the net cages. Some companies have in house service vessels and crews, whereas others hire manned service vessels to perform such work.

There is a development in the industry where specialised service vessel crews are performing operations that were previously performed by operators at the fish farms. Consequently, they take the risk associated with for instance crane operations. This form of specialisation does however also give the operators the opportunity to focus their training on specific operations and become experts in certain areas. It is likely that this kind of specialisation will reduce the operational risk levels.

Well boats are important for transporting the fish, and participate in operations such as lice treatments. Well boats will serve several different fish farms, and the skippers and crew must therefore cooperate well with many different operators. Furthermore, the welfare of the fish has to be protected during the operation.

When it came to challenges that were relevant for simulator training, four areas stood out. First, the risk for work-related injuries. Second, the risk of escape of fish, third, the risk of harming the fish (fish welfare) and fourth, the risk of material damage and production losses.

Looking at the range of operations conducted in fish farming, particular work operations were evaluated. About 30 such operations were detailed and the relevance for simulator training were assessed, including briefs/debriefs in a classroom setting where relevant topics may be taught. This covers operation involving well boats, fish farmers and workboats, service vessels and a combination of these actors. There are operations on mooring lines and anchors, towing of floaters, net cleaning, net mounting, delousing, transport of fish, navigation and mooring inside the fish farm. The majority of the most demanding operations involves safe and sound handling of fish. In the following two examples are presented.

Inspection of mooring lines are performed by service vessel crews. Operational challenges are use of cranes and winches, and handling of ropes under tension. Fatal accidents have happened during such operations [18]. It is therefore an important preventive action that proper risk assessments are performed, as well as safe job-analyses immediate prior to the operation. This may also be provided as a course module in combination with training of safe practice in a simulator exercise.

Delousing of fish is a complex operation. Preparations are made by the fish farmers in that equipment are removed from the fish cage and the fish have to be crowded, i.e. the volume of the net is decreased considerably by lifting the bottom weights and weight cables on the side. This involves extensive use of cranes and several manual heavy tasks for the operators. The delousing has traditionally been conducted in two ways, either by chemical treatment of the fish inside a well boat, or by "wrapping" the net cage into a tarpaulin and adding bathing the fish in the reduced volume of water with added chemicals. The oxygen levels and welfare of the fish have to be monitored continuously. This is also a kind of expertise that is gained with experience. The informants listed fish health and how to assess fish welfare as relevant topics for the classroom part of a simulator training platform.

SCENARIO SELECTION

The aim of the scenarios is to give details on operational conditions, risk factors and possible variations in influencing factors.

For well boats, basic exercises are to navigate to and between cages in the fish farm, go alongside and moor, and after the operations are finished, set off from the fish cage. Typical operations are splitting and sorting of fish, transport of fish and delousing. Table 1 shows examples of training cases for service vessel crews to be implemented in the simulator.

Table 1: Examples of simulator scenario cases for training service vessel crews.

Scenario cases	Level (for each scenario)	Physical environment	Possible "surprises"
1. Mooring to a net cage	Beginner	Calm sea, daylight	Loose ropes, changing currents
2. Navigate towards a net cage	Some experience	Waves, currents, dark	Propel stuck in net or rope
3. Set off from fish cage	Advanced	Mooring lines at shallow depth due to currents	Lose machine power

One of the scenarios, which is relevant for all types of vessels (service vessels and well boats) is maneuvering the vessels close to the net cages. This is particularly challenging for the large well boats because the potential consequences are severe if they interfere with the mooring lines or get the propeller stuck in the net because fish will escape. For the smaller vessels there is also a significant risk for damaging net structures.

In addition to practicing basic skills, different scenario cases where the engine breaks down or ropes get stuck in the propeller, causing a vessel to drift off towards a net cage, allows for practicing problem solving and cooperation.

All crane operations, especially when handling fish cage structures and moorings, but also lifting cargo or equipment, are associated with a high accident risk and will therefore be central in several training cases. Fig. 4 on the next page is an illustration of the scenario "hauling up the net using the crane on board a service vessel". The weight on the crane and length of the arm affects the stability of the vessel, and it should be trained how to deal with this. The stability margins of the vessel should be known and used correctly for safe operations. The theory of vessel stability and how to safely load a vessel will be topics in the corresponding classroom lectures.

Figure 4: An illustration of the scenario "Hauling up the net using the crane on board a service vessel" with a large wave coming in from the side.

SIMULATOR MODELS

A new simulator model for an aquaculture site was developed to provide the following features: 1) contact forces between ship and structure elements, 2) manipulation of the weight system, 3) manipulation of the anchor system, 4) real time simulation of complete site. A visualization of the developed model is seen in Fig. 5.

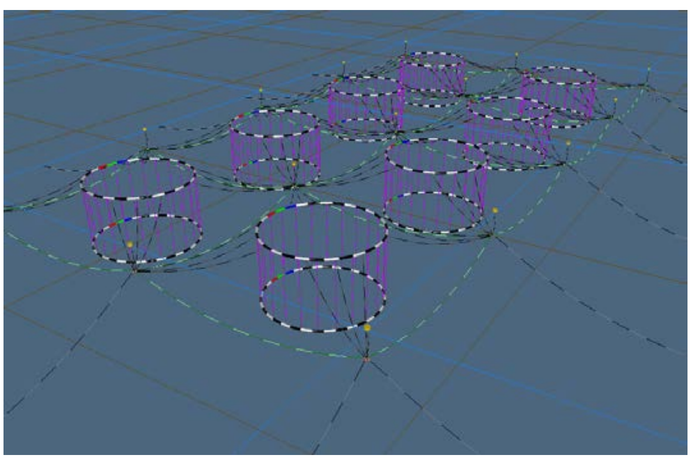

Figure 5: Visualization of the developed model of an aquaculture site. All structure elements reside in the same model and allows the model to have good performance even with a high level of interconnected flexible elements.

The new simulation model was developed with a constraint based structure model where structural forces are enforced by an equivalent control law in each joint [24]. This formulation allows rapid oscillations, particularly in the axial direction, to be suppressed in the solution of the dynamics by selecting the bandwidth of the control law, which enforces structural continuity. The viability of this approach has been shown in [25]. The bandwidth of the structural forces was set to 60 Hz allowing the structure to exhibit the global behaviour expected of an aquaculture site. The structure of the aquaculture site was constructed by joining cables and ring sub-models with joints using the same approach.

The model was parameterized on the number of grid cells in the two main directions allowing it to represent a single 1x1 fish cage and both a standard 2x4 and a 1x8 aquaculture site. Calculation time of the model is dependent on the total number of cells. The ratio between real and simulation time, smaller number implies faster calculation time, on a laptop computer with a 3.0 GHz Core i7-3940MX CPU is seen in Fig. 6.

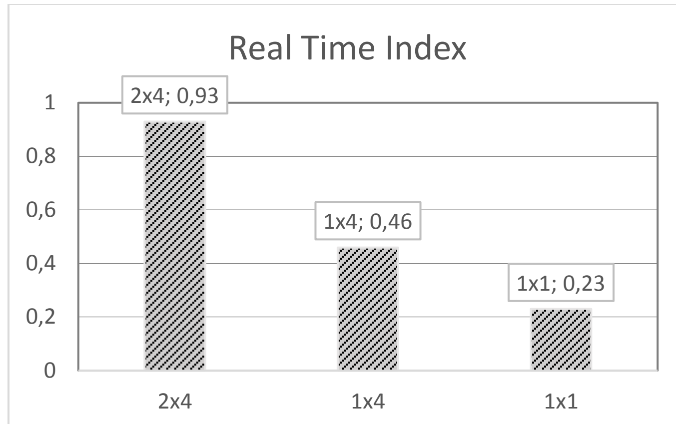

Figure 6: Real time performance of site model vs number of cells in model.

Collision forces are represented by attaching capsule geometries to all cable, buoy and ring elements. An additional capsule geometry is introduced to represent the ship and the geometry with similar length, depth and width. Collision forces are computed by calculating the overlap between only the ship capsule and the capsules on the site. This allows the ship to collide with the buoys and deform all cable and ring structures in the site.

External manipulation of the model is provided by system inputs which allows the weight system cables the be retracted towards the floating collar. The connection plates can similarly be lifted by application of an external control force. The control force can be formulated as a feedback control law between a desired, external position, and the actual position of the connection plate.

CONCLUSIONS

The Norwegian aquaculture industry is associated with high accident risk levels compared to other industries. Escape of fish is a challenge for the industry. There is a potential for increased safety for both humans and fish if operators can practice standardized operations in a safe environment. Existing simulators are not suited for this context.

In this paper, results from a research and development project aimed at developing a realistic simulator-based training platform for fish farming are presented. A wide range of operations implying elevated risks for fish and personnel, e.g. delousing and handling of net cages, have been assessed with regard to challenges and training needs for the personnel. On this basis training scenarios have been sketched. Functional requirements to the simulator models have been derived from these scenario descriptions.

Mathematical models have been developed for simulation of the net cage and the anchoring structures, how they respond to waves, currents and other external forces, under different circumstances and unexpected errors that might occur. The simulator to be developed will thus provide a valuable tool for realistic training of well boat crews, fish farm and service vessel operators.

A simulator for the training of complex marine operations would also be beneficial for the designers and suppliers of aquaculture technology. Their new concepts can be tested in the simulator and improvements can be made during the development process. The future customers could also give their input and test whether the equipment suit their needs. Finally, realistic testing of new operational procedures and safety barriers can be performed in the simulator environment in order to evaluate whether they function and perform as intended.

ACKNOWLEDGMENTS

The paper presents results from the research project no. 226561 funded by the Research Council of Norway, the MAROFF program. We would like to thank the lead partner, Rørvik Maritime Safety Training Center, Norway, and the industry partners in the Rørvik region, that have contributed with their professional experience regarding the challenges in aquaculture operations.

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