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TOWARDS DEVELOPING A CODE OF PRACTICE FOR OFFSHORE AQUACULTURE VESSELS

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ABSTRACT

In recent years, fish farming facilities and the aquaculture industry are gradually moving towards more offshore (or exposed) locations, bringing new opportunities to increase their value creation through better production conditions regarding the aquatic environment due to space availability and water quality which can be extremely beneficial, resulting in more stable farming conditions. This study is focused on the demand for a code of practice for the design, operation, and survey of aquaculture vessels, particularly in offshore regions.

However, offshore aquaculture requires the vessels to operate in more severe sea states, which require the farming structure, station-keeping systems, and vessel-farming site interaction to be more robust. On the other hand, the specific *operations demanded from a fish farm vessel, such as net handling, anchoring, mooring, towing, delousing, feeding and live fish transporting, require specific guidelines that can cover the vessel and system design as well as their safe operation.*

Relevant rules and regulations from national and international guides and standards, including the Australian National Standard for Commercial Vessels (NSCV), and rules and guidelines of classification societies, are reviewed. Furthermore, the study discusses the current research studies centred around aquaculture vessel design and operations, including crew transfer vessels for fish farms, bunkering and alternative fuel sources. Finally, this paper aims to identify the current gaps and similar guidelines and research concepts towards developing a code of practice for aquaculture vessels. A framework for developing such a novel code of practice for offshore aquaculture service vessels in line with the other current efforts on the safety of aquaculture operations will be discussed.

Keywords: aquaculture, vessels, offshore.

1. INTRODUCTION

Fish farming facilities are traditionally located in sheltered areas along the shoreline. However, this industry has gradually moved towards more offshore (or exposed) locations in recent years. The terms "sheltered", "exposed", and "offshore" have no uniformly accepted definition and are used and interpreted differently. In Norway, for example, exposed refers to an area with more extreme sea states than usual sites. According to Standards Norway [1], five distinct exposure classes are specified based on significant wave height (H_S), peak wave period (T_p) and current velocity. However, this classification was insufficient as the probability of occurrence for these conditions is not considered [2]. Furthermore, exposed aquaculture sites experience more severe sea states, which require the farming structure, mooring systems and vessels to be more robust. Despite the challenges, aquaculture companies continue to focus on farming in exposed locations, bringing new opportunities to increase their value creation through better production conditions regarding the aquatic environment. For instance, the space availability and water quality in exposed locations can be extremely beneficial, resulting in more suitable farming conditions. In addition, the environmental conditions can reduce sea lice problems on farming species. If fish escape occurs, its effects on the ecosystem and wild species may be less than in sheltered locations as the fish will scatter over a larger area.

Different species are farmed in offshore aquaculture. These species can be categorised into three main types: finfish (e.g., barramundi, and salmon), shellfish (e.g., mussels, and oysters) and seaweeds (e.g., giant kelp). Finfish species need to be fed; to do so, manufactured feed need to be provided, often in the form of pellets. This is called intensive aquaculture [3], which involves intervention in the growing process. On the other hand, shellfish and seaweed either feed on natural resources or absorb nutrients dissolved in water. For example, shellfish, normally left to grow on the seabed, filter the water, separate food, and then feed on them. This type of aquaculture is extensive aquaculture which allows the species to grow on their own. These differences in aquaculture farming require specific vessels and equipment. Feed vessels are required for finfish farms to transport the food from the shore to the site. Shellfish and seaweed farms use harvest vessels to collect the species.

2. AQUACULTURE VESSELS

Generally, aquaculture vessels can be categorised into two main types according to their flexibility for different operations: specialised and multi-purpose vessels. A specialised vessel is designed to perform only one task or a set of tasks, and its systems, equipment and configurations are optimised to perform these missions, which perform with a high level of efficiency in return. On the other hand, a multi-purpose vessel can perform different tasks and missions, giving the vessel a range of operational flexibility and adapting to various needs and demands. However, the multi-purpose vessels are normally larger than the specialised vessels due to providing space and housing different equipment for multiple missions. Therefore, a multi-purpose vessel is often less optimal for a specific mission than a specialised vessel, reducing performance efficiency [4]. It should be noted that this trend is not specific to aquaculture vessels, and naval ships have moved towards multi-role vessels which are inevitably larger, more expensive and less capable for a given mission than specialised single-role alternatives. However, they are highly efficient in keeping down the total number of hulls to deliver the total military commitment of a navy [5].

Three different vessel classes regularly service existing aquaculture sites; wellboats (fish carriers), feed carriers and service boats. Wellboats are limited to operations with the marine species, including transporting, treating, moving between sites or cages and refilling supplies while ensuring the species' welfare. Wellboats incorporate containers, known as wells, where live species are stored. The wells can be connected to an open or closed piping system for water recirculation. These vessels are large and complex and interact directly with the floating collar and the cage. Recently, the size of these vessels has increased to the extent that they barely fit between the collar and moorings and induce large forces on them. However, wellboats have a key role in the aquaculture industry with the range of operations they can perform, and they are being developed according to regulations for the species' welfare. This may have a huge impact on the older generations of wellboats due to the lack of equipment or technology, resulting in the construction of newer types [6].

The feed vessels transport feedstock from the production site or shore to the farm. The feed is usually transferred to a feed barge with cranes or hoses. Today, some feed vessels use dynamic positioning during the transfer in order to avoid mooring. Besides these vessels, various barges and work platforms are also employed in a farming site for feeding purposes. A feeding vessel design can be hexagonal, minimising resistance to wave forces and ensuring good stability in extreme sea conditions [7].

Service boats are the regular day-to-day operational vessels used at a site and support larger vessels such as wellboats during their operations. Today, the most common aquaculture vessels are less than 15 m long and equipped with a high-capacity crane [4]. These vessels are dimensioned to allow them access throughout the entire site. Their draught is restricted to avoid interference with the mooring, and they have a reduced freeboard for easy access from the deck to the floating collar. Regarding the hull form, catamaran designs are vastly popular, providing a large deck as a working area and a good stability performance [4]. In addition, a catamaran hull form has appropriate manoeuvrability and can be used for cage installation or mooring.

In addition to these main types of aquaculture vessels, a range of vessels with flat decks have been introduced to serve aquaculture sites, mainly for shorter-term operations, including moorings, net changing, stock cleaning, grading, harvesting, and feeding [7]. For example, Galician shellfish have their own local timber vessels with wheelhouses forward and aft of the hull to provide working space on deck [7]. In addition, in Scotland and Norway, a range of flat-bottomed square stern steel crafts (similar to semisubmersible vessels) have been utilised for aquaculture demands in the local areas. These vessels can hold between 50-400 tonnes of food and deliver 20-80 tonnes daily [7]. FIGURE 1 presents examples of different types of aquaculture vessels.

3. RULES AND REGULATIONS

The rules and regulations for designing a vessel are typically based on its gross tonnage (GT) and/or length, the number of passengers, or the operating speed. However, the American Bureau of Shipping (ABS) has recently published guidelines for building and classing aquaculture service vessels [8]. This guideline applies in conjunction with the ABS Rules for Building and Classing Marine Vessels (Marine Vessel Rules) and other Statutory Regulations and covers the design and construction of unrestricted self-propelled aquaculture vessels [8]. The ABS guideline has been drafted around five classification elements: structures, subdivision and stability, fire safety measures and systems, equipment and navigation, and vessel systems and machinery.

Besides the ABS guideline, there are no other standards specifically for aquaculture vessels, and they are classed based on existing regulations. For instance, vessels with an overall length between 8 and 24 metres or GT under 500 in Norway are categorised as small cargo ships **[9]**. In contrast, vessels above 24 metres or GT above 500 should be designed based on "Regulations on shipbuilding" **[10]**. These regulations include the general arrangement, construction, maintenance, equipment and machinery, and vessel safety systems requirements. However, most sections of these standards have referred to other regulations, such as those made by DNV and BV, while specific requirements and criteria are mentioned in others. Therefore, the Norwegian Standards can be used either as primary or supplementary regulations for the design and operations of aquaculture vessels. Until 2015 in Norway, all vessels with a length less than 15 m were exempted from following any regulations regarding construction and inspection; therefore, a vast majority of aquaculture vessels, particularly service boats, were built under 15 m to reduce the compliance cost [11].

Support vessels

Utility vessel

Credits: Damen Group

Support vessels

Credits: Neptune

Workboats

Credits: Marinnor Company

FIGURE 1: DIFFERENT TYPES OF AQUACULTURE SERVICE VESSELS.

However, the revised regulations in 2015 due to safety concerns include all vessels above 8 m to be approved and certified before construction. The main reason behind the change was safety issues, particularly inconsistency between the size and vessel design and equipment capacity (normally higher than the vessel's performance) and as a result, the type of operations was not suitable for the size of the vessel [11]. These challenges were noticeable in the stability during different operations. Today, there are two categories of vessels in the Norwegian Standards: The first category includes vessels with an overall length between 8 and 24 metres and GT under 500, which are considered small cargo vessels [9]. Aquaculture service vessels typically lie in this range. Such vessels normally have a large deck area (low length-to-breadth ratio), restricted draught to avoid interference with the mooring lines, sufficient stability for operations and reduced freeboard to ease access for the crew between the deck and floating equipment [12]. The second category (vessels above 24 m) mainly includes other types of aquaculture vessels, particularly those working in exposed locations for operations such as anchor handling and mooring. The size of vessels in this group affects their manoeuvrability, mainly interfering with the mooring system or the farming cages. To reduce this interference, service vessels are used to assist them during their operations [12].

The Maritime Safety Committee (MSC) of IMO recently adopted a new chapter to be included in SOLAS as Chapter XV. This chapter, with the new Code for Industrial Personnel (IP Code) and with assistance from the Code of Safety for Special Purpose Ships (SPS 2008), will provide the minimum safety standards for ships that carry industrial personnel, as well as the ship crew, and address specific risks of maritime operations within the offshore sectors, including aquaculture and other similar activities [13]. In this new guide, aquaculture will be considered an industrial activity; therefore, the industry must comply with the corresponding regulations [14, 15].

The National Workboat Association (NWA) represents workboats' owners and operators, including crew transfer vessels in the United Kingdom. This association has a guide for operators, charterers and contractors in the renewables, oil and gas and marine civils industries for safe and effective crew transfer vessel operation, management and crew competency **[16]**. Their guidelines for the safety and management of crew transfer vessels can also apply to the aquaculture industry.

4. STATUS OF AUSTRALIAN REGULATIONS AND STANDARDS

In Australia, the Navigation Act 2012 and the Marine Safety (Domestic Commercial Vessel) National Law Act 2012 are the two primary pieces of legislation dealing with marine vessels. The Navigation Act 2012 covers international ship and seafarer safety and protection of the marine environment related to shipping and seafarers' actions in Australian waters. As authorised under the two Acts, the Australian Maritime Safety Authority (AMSA) inspects and enforces national and international standards for the vessels. For compliance purposes, AMSA categorises vessels under different categories based on their use and operational areas. For example, aquaculture vessels are categorised under Class 3 (fishing vessels). Further categorisation is based on their operational area, as presented in TABLE 1 [17]. If a vessel does not have a common hull form, operation or propulsion system of similar vessels, AMSA may categorise the vessel as a novel vessel [17]. When the vessel length is 35 m or above, it must be designed and surveyed based on a classification society standard and Recognised Organisation (RO) as per Marine Surveyors Accreditation Guidance Manual 2014 [18].

TABLE 1: OPERATIONAL AREA CATEGORIES IN PART B OF NSCV [17].

Category	Operational Area
A	Unlimited domestic operations
B Extended	Extended offshore operations
B	Offshore operations
C	Restricted offshore operation
C Restricted	Restricted offshore operations - specified Areas
D	Partially smooth water operations
E	Smooth water operations

5. MAPPING OF MAIN VESSEL FEATURES

TABLE 2 presents an aquaculture vessel's main features and the rules it must comply with. This table is based on the ABS Guide For Building And Classing Aquaculture Service Vessels [8] and shows that, in most parts, the existing classification society (CS) rules can be applied to aquaculture vessels. The table is based on ABS rules, but they can be replaced with other classification society standards. The sections that require specific rules for aquaculture vessels are live fish tank water control, delousing treatment, feeding, food safety management, and live fish health and welfare during transport. In addition, these sections can adopt standards based on national or international guidelines or practices.

6. AQUACULTURE VESSEL OPERATIONS

A wide range of operations are performed in an aquaculture site which includes net handling, delousing and disease handling, cleaning or disinfection of farm structures and systems, inspection, maintenance, repairs, construction, anchor handling and mooring, towing, operations support, emergency response and rescue, supply and transport. Depending on the type of operation, different vessels with capabilities and equipment are used either in a stationary position or in motion. Consequently, operations and interactions between the vessel and the aquaculture site are challenging and risky [19]. Therefore, the safety and reliability are affected by all these parameters such as the slow rate of development of aquaculture vessels including technology, operation and design when transiting from sheltered to exposed sites [11]. The main challenges are vessel-structure interaction (direct or indirect interactions such as navigating between the cages) and relative motion, hydrodynamic performance, structural integrity and equipment installations [20]. Furthermore, rough seas and difficult working conditions in exposed areas add to the operational challenges, typically complex with several humans and equipment working together on the vessel and the floating collar. Therefore, the safety and reliability of the operations are affected by all these parameters. In fact, Human Factors (HF) need to be considered in ship and machinery design to help reduce potential human errors [12]. Human-Centred Design (HCD) is a method that can include Human Factors in a design. According to ISO 9241-210 standard [21], six principles should be considered during an HCD:

- The design is based on an explicit understanding of users, tasks and environments
- Users are involved throughout the design and development
- The design is driven and refined by user-centred evaluation
- The process is iterative
- The design addresses the whole user experience
- The design team includes multidisciplinary skills and perspectives

In maritime applications, Lloyd's Register has published several practices that can be utilised for HCD [22-25]. In these practices, the human element is divided into two categories: Human Resources and Human Factors, with their details presented in TABLE 3 and TABLE 4, respectively. In addition, Maturana and Martins [26] proposed a technique for the early consideration of human reliability in the design phase of oil tanker operations, which can be adapted for use in aquaculture vessel operations. The technique involves applying a generic model to study scenarios of collision. This model incorporates human factors such as workload, situational awareness, and decision-making processes. By simulating different collision scenarios and analyzing the role of human factors in each one, designers can identify potential areas of improvement in vessel design and operation that may improve human performance and reduce the risk of accidents.

In addition to the technique proposed by Maturana and Martins, there are other techniques that can be employed in the design phase of aquaculture vessel operations to consider human performance such as simulation and modeling tools which can be used to test different vessel designs and operational scenarios, allowing designers to identify potential issues and opportunities for improvement before the vessel is built. Simulation and modeling can also be used to study human factors such as workload, situational awareness, and decision-making processes, allowing designers to optimize vessel designs for human performance. Task analysis can also be another option involves breaking down the tasks and activities involved in operating an aquaculture vessel into smaller, more manageable components. This allows designers to identify potential areas of difficulty or risk, and develop solutions that improve human performance and safety.

However, vessel operability has not been specifically defined as various criteria such as operational performance, seakeeping performance, structural performance, and economic performance affect its assessment. For instance, it can be defined as the ability to perform a mission safely [27], within a certain time and motion limit [28] or within sea states' limits [29]. Aquaculture vessels experience uncertainty in the frequency and stochastic processes in the operations due to the handling of live species; hence measuring their operability becomes significantly challenging [30]. In the offshore industry, vessel performance is commonly assessed by using sea-state data from the area and estimating the limiting sea-state curve for a single operational criterion [31].

7. PREVIOUS RESEARCH STUDIES

Several research studies have been conducted to understand these challenges from different aspects, including design, operation, and safety. For example, Paleo et al. [7] reviewed different types and specifications of aquaculture vessels. The authors stated in this review article that the stability of aquaculture vessels is a major concern alongside cost, durability and seaworthiness. To ensure these elements are met, the aquaculture industry can develop solutions based upon offshore oil technology and their systems with the latest telecommunications and control systems to overcome the challenges in creating opportunities in offshore aquaculture. Furthermore, in another review article, Bjelland et al. [11] reviewed the technological challenges in four areas in class 3 of Standards Norway [1], with Hs = 2.5 m and a current speed of 1.0 m/s. The fourth area of this study was vessel design for exposed operations, in which the vessel and its equipment must be designed for safe and efficient operations in exposed locations. The study categorised this area into status and challenges group and research needs group. The challenges group was sub-categorised into:

Industrial status and challenges: Three different classes of vessels regularly work at an exposed site: wellboats, feed carriers and service boats. Due to regulations, these boats were limited to 15 m in length. However, as the industry requirement amplified, the capacity of onboard equipment such as cranes and winches also increased. At the same time, the limit for the vessels' length remained unchanged, which resulted in incompatibility between the equipment and service boat performance and higher operational risks.

Research status and challenges: Vessels in exposed sites must withstand extreme water and wind loads, with seakeeping must be retained under these conditions, which is dependent on the hull design. The knowledge behind small water-plane twin-hull (SWATH) and wave-piercing vessels, merchant ships, and the offshore energy industry, along with analysis software such as computational fluid dynamics and simulators, should be utilised to optimise the design of aquaculture vessels.

In terms of research, four tasks were mentioned that require further research, including new designs for vessels and their seakeeping capabilities, the interaction between the aquaculture structures and vessels using hydrodynamic-structure simulations, analysis of critical operations to assist the design, and logistic optimisation regarding storage personnel and equipment.

In 2017, a research plan was established at the Norwegian University of Science and Technology (NTNU) with the assistance of SINTEF Energy Research to address a few challenges in exposed aquaculture sites. In one of these research activities, Stemland [32] studied vessel behaviour and performance during the interaction between the vessel and the aquaculture structures using VERES software. Macho 40 was selected as the case study to acquire the limiting wave conditions used as input in the VERES model. The author used the methodology introduced by Fathi [33], in which the vessel geometry is converted into transfer functions, and in conjunction with the wave spectrum, the vessel response spectrum was generated. Operability criteria were then fed into this spectrum, and the limiting wave conditions were obtained. The outcome of this investigation revealed that the heading wave is one of the main parameters affecting a vessel's operational limit. Using the same numerical approach, Nørgaard [30] evaluated the hydrodynamic operability of a service vessel using multiple performance indicators. In addition, the vessel response was analysed using hydrodynamic VERES software. The study also considered non-simulation-based evaluation. The operational scenario consisted of one fish farm, one port, and one service vessel (Macho 40) navigating from port to site. The results of the non-simulation indicated that weather forecasts substantially affect the operability.

Moreover, the transit time and operation duration should also be considered when assessing a service vessel's operability. On the other hand, based on the results from the simulation-based approach, operability should be defined as the ratio between operations performed and operations performed during perfect weather corresponding to an operation demand. In a similar study, Sjøberg and Lund [20] assessed the operability and operational limits of three different designs (one monohull vessel and two catamarans) of aquaculture vessels using discrete-event simulation with hydrodynamic vessel response analysis. In order to calculate the motion responses, VERES was used with the two-dimensional strip theory developed by Tuck et al. [34]. This strip theory converts the three-dimensional ship hull into a series of two-dimensional strips, and as a result, the forces and motions of a three-dimensional ship can be identified from a series of two-dimensional analyses. This study assessed how different vessels performed at different exposure and which criteria dictated their operability. For example, the monohull's operability was mostly limited by roll motion, whereas the catamaran was limited to motion sickness incidence at the aft perpendicular. Furthermore, the catamaran generally showed the best overall operability than the monohull vessel for conditions tested.

As part of the NTNU research plan, Nekstad [4] used the concept of modularisation to develop a framework for designing a flexible aquaculture service vessel. The framework enables the vessel platform to house different systems and equipment. Depending on the vessel's mission, equipment arrangement, and structural compatibility, certain devices onboard the vessel can be used to fulfil the mission. The mentioned framework was tested in a case study, which identified a vessel platform that can accommodate the systems, equipment and configuration required to perform 16 different missions. FIGURE 2 shows the design algorithm for such aquaculture vessels. The first steps of the design involve finding the vessel's purpose, needs and stakeholders' requirements. Then the operations that are planned for the vessel must be identified. Based on these data, the working area (platform) required for the operations, as well as the set of equipment, need to be specified, which will define the vessel's design. By combining the platform with the correct equipment, the vessel can have operational capabilities matching the stakeholder requirements [4]. During the design, it must be ensured that the vessel and the platform can withstand and remain stable under environmental and working loads.

Following the design of aquaculture vessels, in a risk-based design attempt, Andersen [12] found a suitable deck platform design for an offshore farming service vessel (Macho 40 vessel). The author proposed three concepts for the design: Concept 1 was a design capable of performing various operations with low risk possible, concept 2 was defined to eliminate risk in anchor handling and mooring operations, and concept 3 focused on reducing the risk to the crew. Since the personnel risk category has a major impact on a service vessel operation, it was concluded that concept 3 should be selected for the deck design of an aquaculture service vessel, with anchor handling and mooring being the most hazardous operations. Besides, this concept adds to the safety of material and the environment and lowers the risk of lifting operations.

Furthermore, Hornsletten [6] developed an optimisation model for the aquaculture industry's wellboats composition and routing according to future transportation demands and requirements. The model is deterministic in order to minimise the costs of operating a fleet of wellboats while ensuring all demands are serviced. The model was very simple, taking inspiration from Vehicle Routing Problems with Pickup and Delivery and Time Windows (VRPPDTW) and tested under different scenarios, including seasonal scenarios, to evaluate and determine a fleet composition suited for each seasonal demand and additional tasks scenarios to evaluate the effects of fleet composition and routing. However, the author mostly assumed the time and cost elements used in the calculations and focused on the model's applicability; therefore, the model might not represent a real-world problem.

TABLE 2: SUMMARY OF DIFFERENT PARTS AND THEIR REFERRED RULES BASED ON ABS GUIDELINES.

Feature	Section	Rule Reference
Structures	Hull	CS Hull Structures and Arrangements CS Offshore Support Vessels for Specialized Services CS Specific Vessel Types
	Supporting Structure for Cranes	CS Offshore Support Vessels for Specialized Services
	Refrigerated Cargo Spaces Refrigerated Sea Water Tanks	CS Specialized Items and Systems
Stability	Intact and Damage Stability	CS Subdivision and Stability CS Specific Vessel Types SOLAS Chapter II Torremolinos Safety of Fishing Vessels
Fire Safety	Structural Fire Protection	CS Fire Safety Measures
	Fire Safety Systems	CS Fire Safety Systems
	Refrigerated Cargo Spaces, Refrigeration Machinery Spaces or Refrigerant Storage Space	CS Specialized Items and Systems
Equipment and Navigation	Anchoring, Mooring, and Towing Equipment	CS Equipment
	Navigation	CS Navigation
Vessel Systems and Machinery	General Requirements	CS Vessel Systems and Machinery
	Refrigeration Systems	CS Specialized Items and Systems
	Ancillary Systems for Live Fish Tanks	CS Piping Systems
	Live Fish Loading and Unloading Systems	CS Piping Systems
	Live Fish Tank Water Control Systems	Aquaculture Service Vessels
	Examination and Testing	CS Vessel Systems and Machinery
Optional Equipment and Systems Certification	Delousing Treatment System	Manufacturer's standard
	Feeding System	National or International Standards or Codes
Surveys	Testing, Trials and Surveys During Construction	CS Vessel Systems and Machinery
	Surveys After Construction	CS Rules for Surveys After Construction
Food Safety Management Systems		ISO 22000 FOOD SAFETY MANAGEMENT
Live Fish Health and Welfare During Transport		World Organization of Animal Health: Aquatic Code Food and Agriculture Organization

TABLE 3: HUMAN RESOURCE CONSIDERATIONS [22].

Parameter	Description
Personnel	Understanding the correct mix of people onboard to operate and maintain the ship and its systems
Manning	Understanding that ships have the number of people required for the safe operation and security of the ship and the protection of the marine environment in both normal and emergencies
Training	Identifying training needs to ensure personnel are competent and familiar with the ship and its systems

In addition to the aquaculture industry, offshore wind farms have encountered similar challenges in their service vessels, particularly crew transfer vessels (CTVs). As a result, a few recent research attempts have been conducted to optimise the CTV fleet towards optimum cost, minimum revenue loss, and maximum electricity generation [35-37]. CTVs are the most effective personnel and equipment transportation method to offshore wind farms, but they face a big issue in their landing manoeuvre. Specifically, the ship's motion while maintaining contact with the turbine fender makes this operation very complex. The most common way is to push against the wind turbine landing area with the vessel bow fender [38]. In this regard, König et al. [39] used numerical simulations for a safe crew transfer within certain conditions. In order to do so, the same strategy was planned in which the vessel and the deformable fender pushed towards the contact area to create a vertical friction force counteracting the wave-induced forces. In this way, the bow can be kept at rest, and personnel can travel to the landing area. Because this is a complicated process, each subprocess was analysed individually. Then, they were integrated into a partitioned solution strategy based on a customised staggered coupling scheme.

TABLE 4: HUMAN FACTOR CONSIDERATIONS [22].

Parameter	Description
Habitability	Company ensures accommodation, washing and toilet facilities, messrooms, group meeting and exercise areas are comfortable, clean (or cleanable) and convivial for all seagoing personnel
Manoeuvrability	Company ensures its ships have the most appropriate manoeuvring capabilities
Workability	Company ensures its ships and systems are appropriate for the proposed work situation (context of use), and that limits will be readily understood by the crew.
Maintainability	Company ensures operational maintenance tasks are rapid, safe and effective to allow equipment and systems to achieve a specified level of performance
Controllability	Company ensures appropriate integration of people with equipment, systems and interfaces
Survivability	Company ensures that there are adequate firefighting, damage control, lifesaving and security facilities to ensure the safety and security of crew, visitors and passengers
Occupational health and safety	Company ensures appropriate consideration of the effect of work, the working environment and living conditions on the health, safety and wellbeing of workers
System safety	Company ensures appropriate consideration of the risks from people using (or misusing) the system

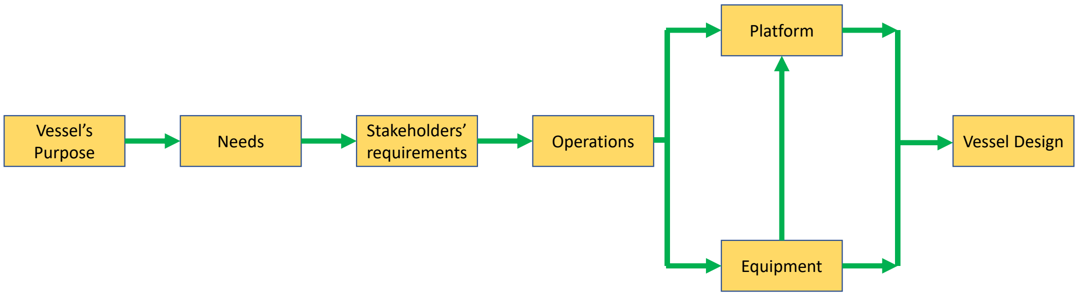

FIGURE 2: AQUACULTURE VESSEL DESIGN ALGORITHM [4].

The economical aspect of CTVs is another area in which researchers are interested. For instance, to reduce the operating costs of such vessels, electric or hybrid drives can be an effective solution to generate or store energy for hydrogen fuel cells [37]. Furthermore, a hybrid system with a direct current (DC) circuit eliminates the need to synchronise generating sets on common rails, reactive power losses, and disturbances from working electrical machines and converters of electricity in the power system of the unit, thus improving the quality of electrical energy in the ship's power grid (Łebkowski, 2020).

The selection of CTVs is also a subject with many interests [35], with many factors, including vessel specification, financial attributes, environmental conditions, and failure characteristics. One of the main issues in operation and maintenance planning is not considering the vessels and their influence on the operation, specifically the failure recovery maintenance scheduling time [35]. Monohull boats, small catamaran vessels, and SWATH vessels are generally utilised in minor maintenance operations, allowing operators to keep minor maintenance operations' costs at optimum level. Catamaran configurations are often the preferred choice by the operators. The most distinctive characteristics of these vessels are high speed, small deck spaces, small crane capacities and safe access to wind turbine structures that will allow operators to take quick actions in the case of unexpected failures. The characteristics of these types of vessels are presented in TABLE 5. In addition, increasing the size of the CTV fleet does not always bring an economic advantage because the production increase cannot compensate for the cost increase if the CTV fleet becomes larger than the optimum level. The capability and operational limitations of the CTVs are also important attributes which significantly influence the fleet size [35].

Another issue related to vessel operations is vessel bunkering. For example, a vessel that serves an aquaculture site often has to bunker at the port. Therefore, the company must decide how much the vessel will be bunkered and what speed they need to travel. First, it must be noted that the bunker fuel consumption rate varies significantly with different vessel sizes and needs to be considered for optimal management decisions [40]. In a research conducted by Yao et al. [40], a management strategy plan based on a mathematical model for fuel bunkering was proposed that accounted for optimal bunkering amount and speed adjustment. This model is for international travel but can also be adopted (with some adjustments) for smaller vessels with speed limits [41, 42].

This challenge also brings to the fore the subject of alternative fuels for the vessels. In this regard, a few other options have been suggested. For example, the use of a hybrid diesel generator-fuel cell power plant conceptually designed for an offshore platform supply vessel was proposed by Díaz et el. [43]. The authors incorporated two 250 kW methanol-fed Solid Oxide Fuel Cell systems onboard a ship whose hull design and the general arrangement were optimized accordingly. Although using such hybrid systems or LNG can decrease emissions, it cannot lead to a zero-emission vessel [43, 44]. Recently, hydrogen has been suggested as an alternative to fossil fuels. In a feasibility study for a research vessel, the technical, regulatory, and economic aspects of a coastal research vessel, Zero-V vessel, powered solely by hydrogen fuel cells, were investigated [45, 46]. First, there are currently no specific rules around the use of hydrogen-powered ships. However, such rules are currently being developed by the International Maritime Organization (IMO) and classification societies. Therefore, the design and construction of such vessels can be difficult with no comprehensive rules. In terms of hull form, the trimaran hull form was selected because it provided the space required for operation and machinery. However, this may not be the case for all types of vessels. To save weight, aluminium can be a better construction material. The 52-metre research vessel was designed to use a fuel-cell electric plant with small lithium-ion bridging batteries for propulsion and electrical power supply.

TABLE 5: DIFFERENT CTV CHARACTERISTICS [35].

Vessel Type	Benefits	Drawbacks
Monohull	Very high speed (30 knots)	Limited passenger
	Reasonably lower charter rates	Limited cargo capacity
	Lower fuel consumption	Uncomfortable for passengers
	High availability in the market	Limited safe access to turbines
Catamaran	High speed (20 knots)	Limited passenger
	Operational H_s = 1.5 m	Limited cargo capacity
	Safe access to turbines	Relatively higher charter rates
SWATH	The capacity of 12 to 60 passengers	Limited cargo capacity
	High speed (20 knots)	Low availability in the market
	Operational H_s = 2.0 m	Relatively higher charter rates
	Safe access to turbines	
	Comfortable for passengers	

The hydrogen fuel cells were arranged into ten power racks, each containing six fuel cells with a total power of 1800 kW. The capital construction cost was estimated to be approximately 79 million US dollars, similar to other modern research vessels of the same size and capabilities, with the hydrogen systems contributing 10% of this cost. However, vessel operation and maintenance costs were 7% higher than diesel-powered types. A comparative study between battery-hydrogen and diesel-electric powered research vessels [47] found that by using only batteries, the vessel could provide 2.5 hours of zero emissions but could not perform any of the planned operations. On the other hand, the hydrogen hybrid vessel provided 23.4 hours of zero emissions and accomplished 74% of the intended operations.

8. STEPS TOWARDS A CODE OF PRACTICE

Aquaculture is one of the most dangerous industries in the world; as statistics show, for example, in Norway, it is the second most hazardous occupation [48]. Working in aquaculture requires exposure to harsh weather, including wind, current, and waves that can cause a high level of vessel motion. This can affect, for example, crane operations and makes them complicated. In fact, the statistical studies between 2010 and 2016 demonstrate that most fish escapes happened during operations, including delousing, handling the sinker tub and dead fish pump, and fish loading and unloading [49]. Furthermore, the technical, operational and geographical challenges can vary according to the farming species and site. Therefore, there are no explicit operational limits and cut-off criteria for high-risk operations; it depends on the personnel to decide. Therefore, such operational limits and systematic processes are widely required.

Overall, the statistics show that the fleet of small vessels has the highest fatality rate [50] and because most of the aquaculture vessels are categorized as small vessels in addition to no specific Work Health and Safety (WHS) procedures for aquaculture operations in Australia, there is a need for guidelines to address the challenges (design, operation and safety).

The development of such code of practice for offshore aquaculture service vessels is needed to be conducted in line with the other current efforts on technologies for decarbonising the shipping industry. The EMSA report provided the level of maturity of each technology for alternative fuels that are arguably suitable for ships (including LNG, H2, LPG, Methanol, Ammonia and Biofuels) as well as safety concerns associated with each type of alternative fuel [51]. Furthermore, the use of fuel cells and electrification options have been discussed. Seafarer skills and qualifications for these technologies are expected to be different from conventional vessels powered by diesel/heavy fuel, and hence the development of a new code of practice should consider the human factor as a central element. In addition, there is a lot of concern in the EU about the safety of fishing vessels, and work needs to be done to improve them [51]. Therefore, adopting fishing vessels' design and operational practices to aquaculture vessels is a big question. Finally, there is a challenge of whether STCW-F for Fishing Vessel Personnel would apply to aquaculture personnel.

This study aims to denote the importance of producing a code of practice that could experience a wide uptake among industry and government; hence, it must include a significant contribution from all sectors of the aquaculture industry. The objectives of the Code of Practice include improving the design, increasing safety, and enhancing the welfare of animals and can be done through these steps:

1. Conducting a comprehensive review of the existing rules and regulations to identify what authorities are considering.
2. Discussing with stakeholders to obtain feedback on current aquaculture practices and guidance standards.
3. Identifying gaps that may require preparation and drafting required guidance.
4. Developing the code of practice for aquaculture vessels based on the review and stakeholders' feedback.

Step 1 – Review: This paper contains the outcome of the literature review, which was focused on aquaculture vessels-relate regulations from the National Standard for Commercial Vessels (NSCV), official publications of the Australian Maritime Safety Authority (AMSA), and rules and guidelines of classification societies, the Special Purpose Ships (SPS) Code developed by IMO, and the Industrial Personnel Ships Code. Furthermore, the study covered the developments of the Norwegian research centre for exposed aquaculture operations.

Step 2 – Stakeholders Engagement: This step focuses on discussing the current state of regulations and the aquaculture demands with relevant authorities, industries, and companies engaged in offshore aquaculture vessel operations. These discussions aim to get their input on the gaps identified through the literature review and will be conducted using interviews and surveys. Interview questions are presented in the APPENDIX.

Step 3 – Investigation of the Gaps: This step investigates any missing information or areas that may require guidance to be prepared and draft the required guidance.

Step 4 – Drafting: The final step is drafting the code of practice for offshore aquaculture vessels with an addendum report regarding the basis for the code of practice and identifying any future direction or bodies of work.

The flowchart of the mentioned steps is shown in FIGURE 3. TABLE 6 also presents the overall mapping of the Code of Practice for Aquaculture Vessels with corresponding references for each chapter. It should be mentioned that ABS reference is the guidelines for building and classing aquaculture service vessels, LR HCD is the Lloyd’s Register Human-Centred Design guideline, IMO IP Code is the Industrial Personnel Code developed by the IMO, and FAO is the Food and Agriculture Organisation.

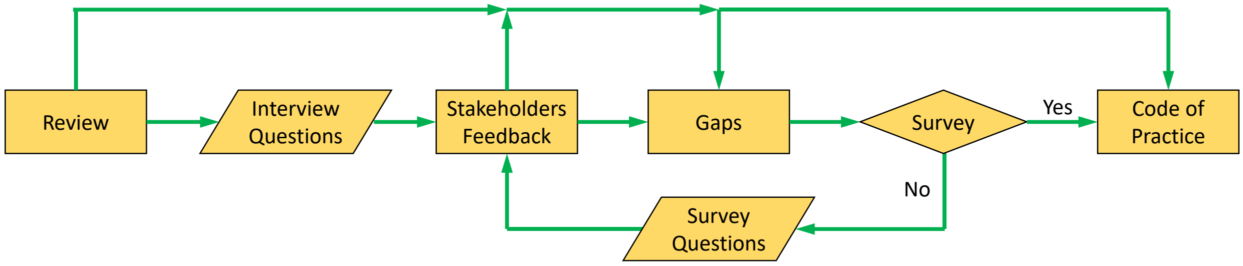

FIGURE 3: THE FLOWCHART OF DRAFTING A CODE OF PRACTICE FOR AQUACULTURE VESSELS.

TABLE 6: OVERALL MAP OF THE CODE OF PRACTICE FOR AQUACULTURE VESSELS.

Code of Practice	**Content**			**References**				
Chapters	**Sub-sections**			**NSCV**	**AMSA**	**ABS**	**Other**	
Chapter 1: Definitions	Scope	Definitions	Application	Part B	Marine order 51	Section 1		
Chapter 2: Structures and Stability	Hull	Supporting Structures	Stability	Part C	Marine order 12	Section 2 and 3	LR HCD	
Chapter 3: Systems and Components (Machinery and Fire Safety)	Operation Equipment	Machinery	Fire Safety	Part C4 and C5A	Marine order 15	Section 4	LR HCD	
Chapter 4: Electrical, Control and Monitoring Systems	Navigation	Electrical	Control - Monitoring	Part C5B and C7	Marine order 27	Section 5, 6 and 7	LR HCD	
Chapter 5: Surveys and Certificates	Pre-construction	Post-construction	Crew Competency		Marine order 31, 503, 504, 505	Section 8	IMO IP Code	
Chapter 6: Food Safety Management	Process	Policies	Managing			Appendix 1	ISO22000	Friends of the Sea
Chapter 7: Live Fish Welfare	Factors	Strategies	Certifications			Appendix 2		FAO No. 5

9. CONCLUSION

Ocean farming in exposed locations will impose new aquaculture vessels' design, operation, and safety challenges. In fact, being in exposed locations will require new technology and equipment for the operations that need to be performed as well as an evolution in the aquaculture vessels' design to handle the environmental loads and to work with the site structures. For example, in order to overcome a specific design in response to the site sea state, introducing additional onboard equipment, such as a dynamic positioning system, will increase the safety level. Furthermore, to reduce the cost of operations, an optimised logistics plan can be very important in exposed locations. New analysis capabilities must be developed in order to analyse aquaculture vessels during operations in an exposed site regime.

Prior to designing an aquaculture vessel, the expected performance (general or operations-related), requirements and safety goals should be specifically assigned. Nevertheless, the uncertainty of the environment at exposed locations will challenge the designer to adapt the design based on these conditions. Furthermore, due to limited research on aquaculture vessels in exposed locations, there is more uncertainty around the design.

On the other hand, the requirements from classification societies and authorities are based on vessels' size, power and gross tonnage. Because the regulations become stricter as they increase, owners and designers try to avoid exceeding the limits to reduce costs. Some examples of such limits include vessels with more than 750 kW power which leads to additional requirements for the crew, specifically a certified chief engineer; vessels with an overall length of 35 metres or more are subjected to class survey requirements; and vessels with GT above 500 should meet SOLAS requirements for cargo vessels. In fact, the vessel's size and shape should be selected and designed based on the missions intended to obtain the maximum capital, operational and voyage efficiencies. The major factor here is designing a multi-purpose vessel with several operational tasks leading to a non-optimal, large and heavy design, increasing investment cost and fuel consumption. In addition, the vessel must be able to manoeuvre and operate in small areas in an aquaculture site, which demands a higher power consumption, suitable propulsor and robust steering design.

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APPENDIX – INTERVIEW QUESTIONS

1- **Design and operation**
  a) What are the main design challenges in these types of vessels?
  b) What aspects make these vessels different from other vessels, such as fishing and offshore support/supply vessels?
  c) Which class (e.g., DNV, ABS, etc.) requirements for the design, construction and survey of such vessels would be applicable?

2- **Regulations**
  a) What Statutory Regulations does your organisation comply with, or aspire to, for the following areas relating to the vessels?
    I. Vessel Design
    II. Health & Safety
    III. Crew Training

  Regulations include – NSCV, Classification Society Rules, SOLAS, Food Safety Management
  a) Are there any additional requirements (within the NSCV or other authority organisations) that such vessels must comply with? If yes, please provide more information.
  b) Do you find the current scope of statutory regulation to be fit-for-purpose, or are there additional aspects that you consider should be within scope?

3- **Human safety, training, and qualifications**
  a) What are the main operational hazards (risks) to human safety (including crew members and other personnel) involved in nearshore aquaculture that designers/operators/shipowners need to be aware of?
  b) What are the main operational hazards (risks) to human safety (including crew members and other personnel) involved in offshore aquaculture that designers/operators/shipowners need to be aware of?
  c) What are the main operational hazards (risks) to assets (including vessels and other facilities) that designers need to be aware of?
  d) What are the levels of competence based on the size required for a certificate of competency for crew members working onboard current aquaculture service vessels?
  e) Is there any other competence required for this particular type of vessel and operation?

4- **Food safety management systems**
  a) Does your organisation adopt a food safety management system? If yes, how is the system implemented throughout the food chain in the operation of aquaculture vessels?
  b) What are the requirements for a food safety management system?
  c) Would ISO 22000 be applicable/sufficient to the aquaculture service vessels involved in the food chain? Please add information/recommendations (if any).

5- **Live fish health and welfare during transport**
  a) What factors need to be considered for live fish health and welfare during transport?
  b) What are support systems needed for live fish carriers/wellboats to comply with live fish health and welfare requirements during transport? Are there any legislative requirements such as RSPCA or Aquaculture Stewardship Council that your organisation adopt for food safety?