REVIEW OF CAGE AND CONTAINMENT TANK DESIGNS FOR OFFSHORE FISH FARMING

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Abstract - Fish farm operators worldwide are planning to move offshore due to lack of available nearshore production sites in heavily utilized coastal zones, where there is increasing community opposition to coastal development and conflict with other usages such as shipping, fishing, tourism, conservation and recreation. Moreover, offshore sites provide more sea space and generally better water quality, which are needed to increase the production of healthy fish. This review paper begins with the definition of *offshore* for fish farming based on a unified viewpoint and proceeds to highlight the challenges faced by going offshore. Next, the paper presents a review of designs of fish cages from conventional nearshore fish farms to next-generation offshore fish farms, which have to contend with a high energy environment. The fish cages may be divided into the open net cage system and the closed containment tank system. The open net cage system can be categorized further into 5 types. The advantages and disadvantages of the various fish cage designs will be discussed. Further, different types of cage designs are compared with the view to guide feasibility of offshore fish farming. Co-location with other synergetic industries is discussed as a possible example of future offshore fish farms.

Keywords – fish cage designs, offshore farming, open net cage, closed containment tanks

1. INTRODUCTION

Fish farming is speculated to have been practiced in China as early as 2000 B.C., and the first historical record of fish farming was written by Fan Lei in 475 B.C. (Villaluz, 1953; Lovell, 1989). Despite over 4000 years of history, fish farming was not regarded as an important food supply. It was only in the 1990s that the world seafood consumption has risen significantly because fish serves as a cheaper protein source for populations in poor countries as well as the belief that fish is healthier to consume than red meat.

Figure 1 shows the dramatic increase in aquaculture production after 1990 (FAO, 2018). Aquaculture production accounted for 47 percent (80 million tonnes) of the total production in 2016. Estimated sale value was about USD 232 billion in 2016 (FAO, 2018). Figure 2 presents farmed fin-fish (both inland and marine) production for food that amounts to 54.1 million tonnes and accounts for 67% of the global aquaculture production in 2016 (FAO, 2018). Although the portion of marine and coastal cultured fin-fish has been relatively small as compared to inland farmed fin-fish, its contribution to the total fish production is rapidly rising for the last decade.

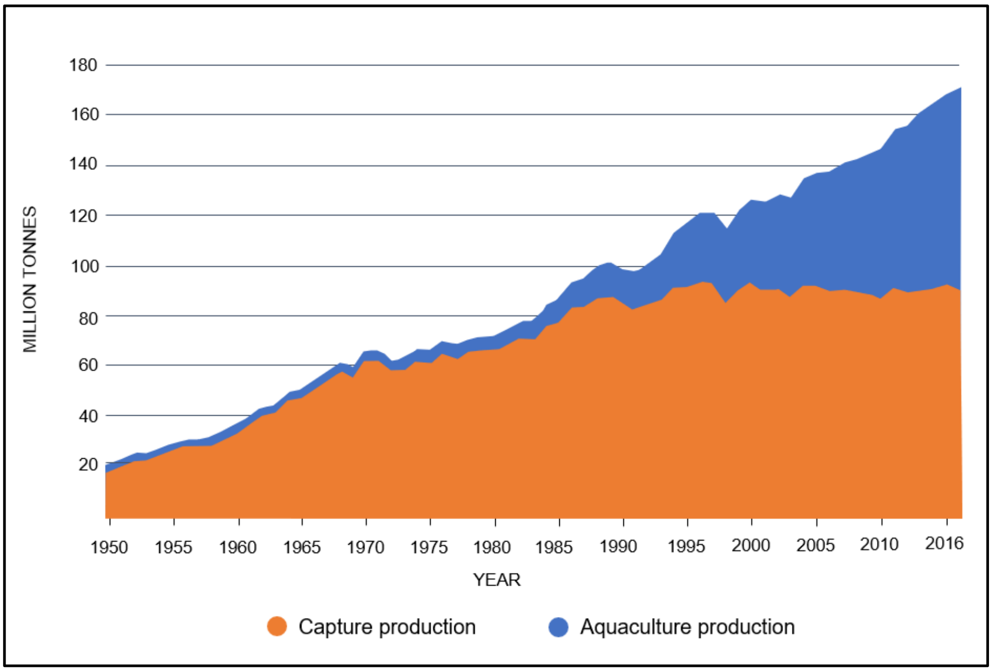

Figure 1: World capture fisheries and aquaculture production (FAO, 2018)

Note: Excludes aquatic mammals, crocodiles, alligators and caimans, seaweeds and other aquatic plants

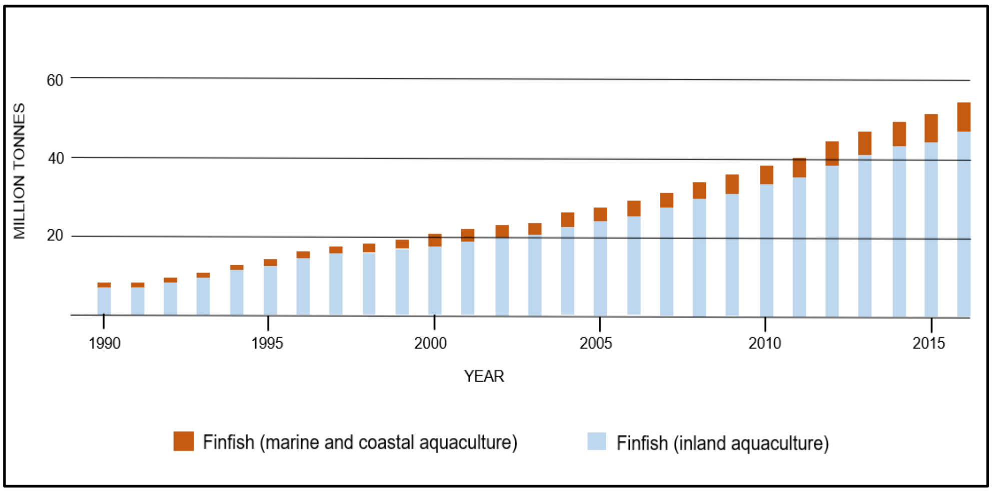

Figure 2: World's production of fin-fish for food (FAO, 2018)

Captured fishes have dominated supply for seafood up to 21th Century, but it has gradually become unsustainable due to overfishing (see Fig. 3). 90 percent of wild captured species are already overfished or fully fished with no potential for increases in production. Therefore, farmed fish is expected to overtake captured fish and it will continue in its impressive growth in supplying the world's protein requirements (FAO, 2018).

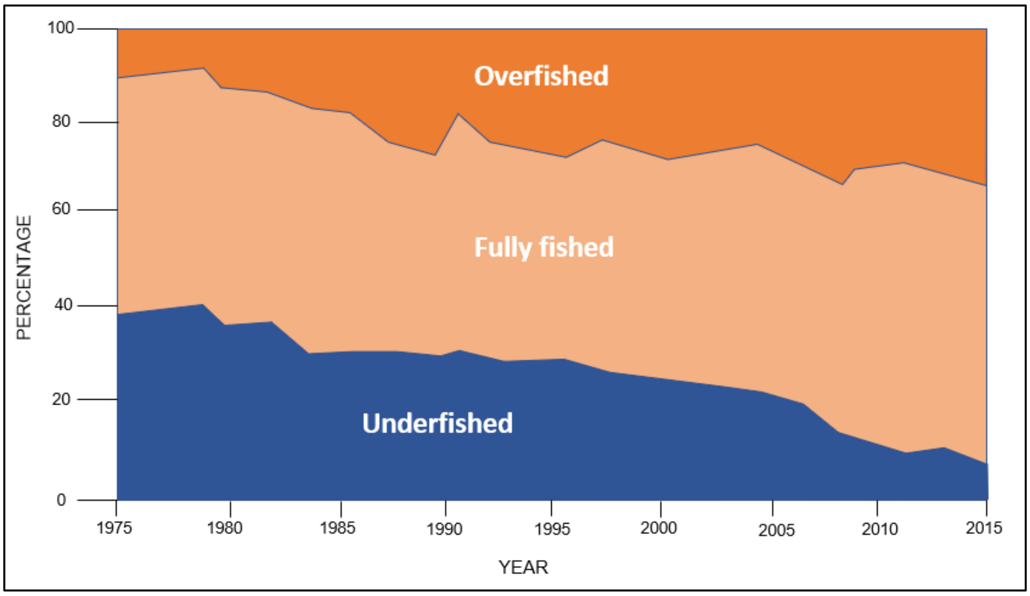

Figure 3: Global trends in state of world marine captured fish stocks (FAO, 2018)

Most marine cultured fish farms are sited in sheltered, shallow and nearshore water, mainly for safe operation and easy access to service facilities for feed, hatchery, storage, maintenance, set-up for processing and transporting harvested fishes. With increasing demand for high production targets and cost-effective operation of fish farms, many nearshore sites have been fully exploited and fish farmers have adopted a high fish stock density for their nets (Huguenin, 1997; Stickney, 2002). Current nearshore fish farming practice has led to conflicts with local communities, conservation and environmental groups. Competition for common sea space in coastal areas has been intensified not only among the fish farmers but also with other sectors such as shipping, tourism, conservation and recreation. The primary criticism from environmental groups towards nearshore fish farming is environmental degradation due to water pollution (Stickney, 2002; Colbourne, 2005; Tidwell, 2012; Shainee et al., 2013; Noroi et al., 2011). In addition, accidents of farmed fish escapement and spread of diseases can threaten native sea life population even more seriously (Huguenin, 1997; Beveridge, 2004; Tidwell, 2012; Taranger, 2015; Verhoeven, 2018).

In response to criticisms from environmental groups and pressure from regulatory authorities, the fish farming industry began to explore sites that will yield sustainable fish production and to make use of environmental friendly operation (Buck, 2004; Kapetsky et al., 2013; Kankainen and Mikalsen, 2014; Bjelland et al., 2015; Holm et al., 2017). It is called offshore sites that offer more spacious ocean for fish farms, reduction of contests with other sea space users, deeper water depth and constant water flow (Huguenin, 1997; Tidwell, 2012; Kankainen and Mikalsen 2014; Holm et al., 2017). The offshore environment can help avoiding accumulation of fish wastes (e.g. uneaten feed or faeces) under cages, thereby preventing proliferation of parasites and diseases. Consequently, it is now clear that exploring offshore sites for fish farming has become an unavoidable choice to keep sustainable and high-quality fish production.

This paper reviews the developments of fish cages from conventional nearshore fish farms to next generation offshore fish farms, which have to contend with a high energy environment. The paper focuses on functional capabilities and economic feasibility of various types of cage design in offshore environment, regardless of the fish species that can be farmed in offshore sites. We shall begin with the definition of *offshore* for the fish farming in Section 2 and highlights the challenges by going offshore in Section 3. Next, we divide the fish cages under the open net cage system and the closed containment tank system. The open net cage system may be further categorized into 5 types. The advantages and disadvantages of the various types of fish cage designs will be discussed in Section 4. In Section 5, the different types of cage designs are compared with respect to their dimensions, fish stock volumes, significant wave heights, distances from shorelines and costs to guide feasibility of offshore fish farming. Also, suggestions of cage designs for future offshore fish farming by co-location with other synergetic industries are discussed. Section 6 gives the concluding remarks.

2. DEFINITION OF OFFSHORE FOR FISH FARMING

Drumm (2010) said "*In general offshore aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbour or shore base is often but not always a factor*." Another definition of offshore, according to the Spanish law, is the sea area outside the straight line joining two major capes or promontories (see Fig. 4). The sea space within these capes is correspondingly defined as inshore (Cabello, 2000).

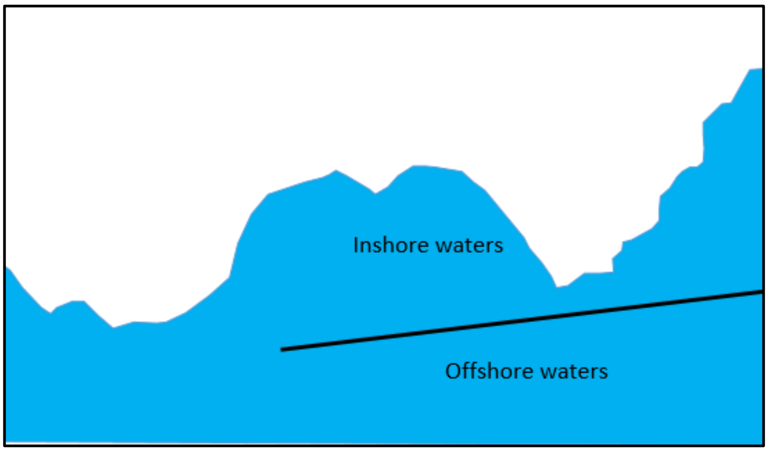

Figure 4: Definition of inshore and offshore waters according to Spanish law

Holmer (2009) defined 3 classes for fish farming sites: Class 1 – coastal farming, Class 2 off-coast farming and Class 3 - offshore farming based on physical and hydrodynamical settings as shown in Table 1. It can be seen from Table 1 that distance from shoreline, water depth, and wave height are the key parameters for defining offshore fish farming. As shown in the Table 2, the Norway Standard of Marine fish farms requirement for site survey, risk analyses, design, dimensioning, production, installation and operation (NS 9415, 2009), the Holmer's class 1 will be regarded as moderate exposure site with respect to the wave height whilst classes 2 and 3 will be regarded as high or huge exposure sites. Shainee et al. (2012) gave basically similar definitions for offshore farming sites while their definition for nearshores sties follow Classes 1 and 2 of Holmer (2009). Offshore Finfish Aquaculture, reported by California Environmental Associates (CEA, 2018), defined the offshore aquaculture in a similar form of Holmer's Class 3 but added further requirements on strong ocean currents and remote operating system.

Table 1: Definitions of coastal, off-coast and offshore farming
(Accessibility <100% refers to limitations in access to the farm due to weather conditions)

		Class 1 Coastal farming	Class 2 Off-coast farming	Class 3 Offshore farming
Physical setting	Distance	< 500m from shore	500m to 3km from shore	> 3km from shore
	Depth	< 10m	10m to 50m	> 50m
	Visibility from shore	Within sight of shore users	Usually within sight	Not visible from shore
Exposure	Waves	< 1m	3m to 4m	Up to 5m
	Accessibility	100%	90%	80%
Legal definitions		Within costal baseline National waters	Within coastal baseline National waters	Outside coastal baseline National/international waters
Major countries with fish farming		China Chile Norway	Chile Norway Mediterranean	USA (Hawaii) Spain (Canaries)

Table 2: Classification of wave by wave height (NS 9415 2009)

Wave classes	H_s (m)	Description
A	0.0-0.5	Small exposure
B	0.5-1.0	Moderate exposure
C	1.0-2.0	Large exposure
D	2.0-3.0	High exposure
E	>3.0	Huge exposure

There are some restrictions on the definition of offshore site for fish farming. For example, Cardia and Lovatelli (2016) recommended that the water depth should be at least 3 times deeper than the open net cage depth and no less than 15m between the cage bottom and the seabed. In addition, Kapetsky et al. (2013) pointed out realistic restrictions imposed on conditions for offshore fish farming such as:

1. Offshore fish farming should take place within Exclusive Economic Zones (EEZ up to 200NM) in order to ensure national governance and to provide for the legal protection of investors. Maximum distance from the coastline to an offshore site is recommended to be 25NM (46.3km) for economic feasibility; considering installation and operation as reported by Jin (2008).
2. Depth thresholds for conventional sea cages is about 25m to 100m based on actual practice and feasible mooring method and costs.
3. Current speed within 0.1m/s to 1m/s for culture fish in the confined open net cage
4. Be dependent on onshore facilities to support offshore grow-out installation (e.g. feed, holding seed, storage, maintenance, set-up for processing and transporting harvested fishes)

Contrary to an aforementioned restriction on distance to within 25 NM, a Chinese company has developed an offshore fish cage (Shenlan 1) and deployed it at 130 NM from Rizhao city in eastern China's Shandong Province (Evans, 2018). Regarding water depth being constrained to 100m, a Norwegian company has designed an offshore fish cage (Ocean Farm 1) which can be deployed in 300m water depth (The Maritime Executive, 2019). In contrast to the dependency on onshore facilities for fish farming, the Australian Blue Economy Co-operative Research Centre posited that offshore fish farms may be co-located with offshore renewable energy systems so that it can be independent of onshore support facilities. So, it can be seen there are many contradictory thoughts on what constitutes the definition of offshore fish farming.

After studying the various definitions on offshore fish farming offered by researchers, we propose a definition that attempts to reflect the general consensus on the parameters defining offshore fish farming. Our definition takes on this form:

> ***Offshore fish farming involves (i) unsheltered sites defined by the seaspace outside a straight line joining two major capes or promontories, at least about 3km distance from shoreline but within the EEZ (ii) water depth that is greater than 50 m or more than 3 times the cage height and no less than 15m between the cage bottom and the seabed, (iii) current speed within 0.1m/s to 1m/s and (iv) wave height exceeding 3m.***

Note that the above definition of offshore fish farming is meant for an initial design of offshore fish cage. There are other factors such as environmental, ecological, other regulatory issues and fish health that have to be considered in the final design of an offshore fish cage.

3. OFFSHORE FISH FARM DESIGN CHALLENGES

There are many design challenges faced in offshore fish farming which have been neither clearly identified nor researched rigorously. As a result, fish farmers are not fully confident about moving offshore for fish farming.

It is crucial that we recognise the design challenges in offshore fish farming as they affect the running costs, productivity, fish mortality, HSE (health, safety and environment) for workers. A good offshore fish cage design should consider environmental risks of the selected farming site and provide sufficient space for healthy fish, possess durable strength and require easy maintenance. These features also have substantial importance to be considered for the well-being of the fish and for the optimum fish growth. It is believed that there are 7 major challenges for offshore fish farming:

(1) water depth,
(2) current speed,
(3) wave action,
(4) sea bed condition,
(5) accidental storm incidence
(6) conducive environment for fish welfare
(7) infrastructure and economic sustainability

3.1 Water depth

Water depth affects installation and maintenance costs for the anchoring and mooring system. The length of the mooring lines is usually three to five times of the water depth. Therefore, deeper depth requires more costs on anchoring and mooring system (Cardia and Lovatelli, 2016; Forster, 2013). The cost for surveying the seabed at such larger water depths will also be high.

On the flip side, a large water depth can lessen the concentration of waste sediment in the area around fish cages (see Fig.5). Since water gets into the cage not only through the sides but also through the bottom, by keeping the cage bottom clear is essential to ensure pristine water for fishes (Chacon Torres et al., 1988a). Moreover, a deeper water depth allows one to have a much higher fish cage that gives more space for fish movement and lessen the probability of fish disease. It also allows fish to move to deeper and calmer water zone during a storm.

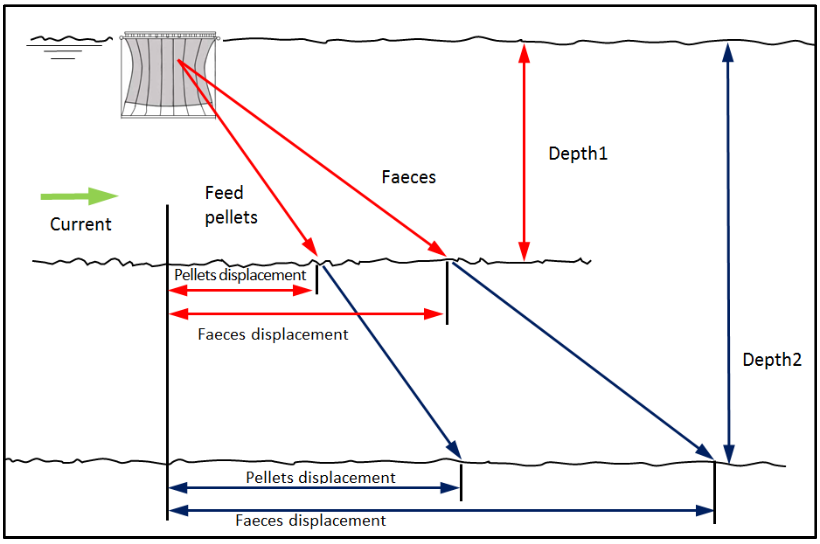

Figure 5: Influence of depth in solid waste displacement on seabed below cages (Cardia and Lovatelli, 2016)

3.2 Current speed

Despite current flow is essential for farming fish in cages for replenishment of oxygen and removal of organic waste, high flow rates may result in detrimental impact on both cage system and fishes. Especially for a flexible open net cage system, horizontal drag forces exerted by current on the cage can reduce the internal volume of the cage. It causes excessive strain on cage collar and increases tension on mooring lines (see Fig. 6). Moreover, under an excessive current flow, fish may spend too much energy for swimming as well as suffer from unacceptable losses of feed (Beveridge, 2004). Consequently, fish growth is curbed and the risk of mortality increases.

In practice, current speeds in the range of 0.1m/s to 0.6m/s have been found to be satisfactory for salmon fish farming (Gowen, 1990; Beveridge, 2004; Kapetsky et al., 2013). Johansson et al. (2014) pointed out the high degree of plasticity in salmon swimming behaviour to adapt to intermittent and strong water currents. However, sites where the current speed exceeds 1m/s are not generally recommended (Gowen, 1990; Beveridge, 2004; Kapetsky et al., 2013). By introducing a finer mesh net (high solidity net), one can reduce the current speed. However, it will increase drag force that will require more strengthening for the cage design. (Moe-Føre et al., 2016)

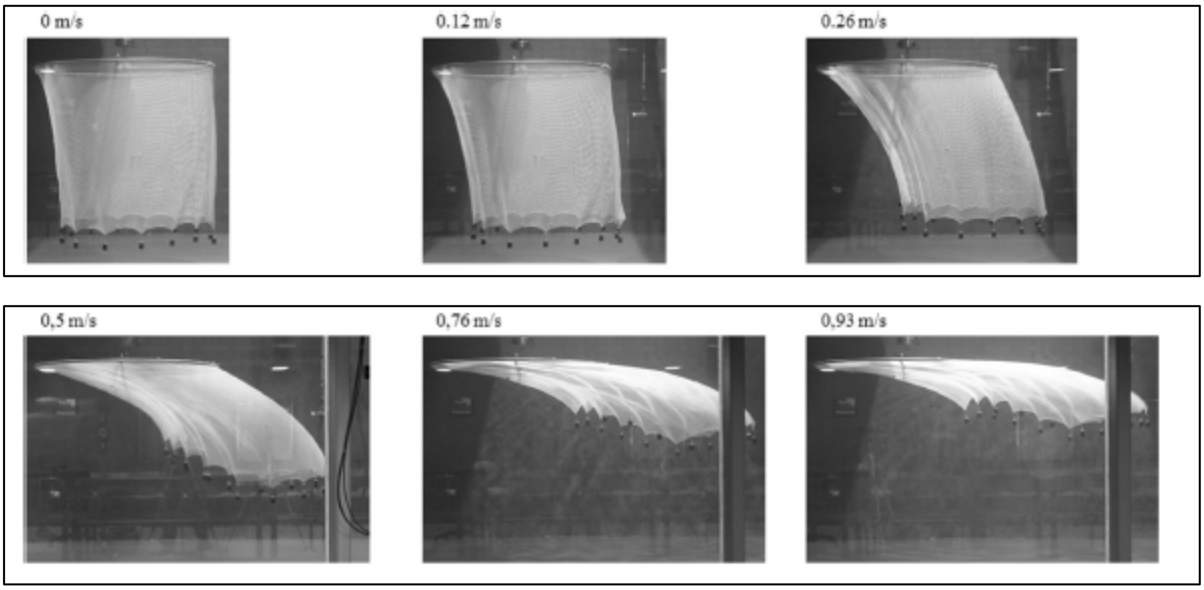

Figure 6: Net cage models subjected to increasing flow velocity
(Moe-Føre et al. 2016)

3.3 Wave Action

Excessive wave action in offshore sites not only damage cage structures and moorings, but it may also injure fish. A severe wave condition can interrupt a farmer's routine operation or even placing the farmer in a hazardous situation.

In order to control the risk of wave action, one approach is to modify the environment so that the effects of waves are reduced by using a system of breakwaters (Dai et al., 2018). Another approach is to make cages able to withstand the extreme environmental conditions or enable fish farm operators to take evasive action by submerging fish cages during bad weather (Beveridge, 2004).

Although modifying the environment can be the most challenging, it is the most effective method. Breakwaters are often used to reduce the effects of waves on coastal marine facilities such as harbours, marinas and aquaculture farms (McCartney, 1985; Dai et al., 2018; Kato et al., 1979; Beveridge, 2004). Breakwaters may be divided into two primary types, i.e. fixed bottom-resting breakwater and floating breakwater. The former structure is usually made from concrete or rubble mound but they are not so suitable for fish farming due to their interference with prevailing currents, difficulty in installing on soft seabed, hard to modify once constructed and restricted to shallow waters. On the other hand, floating breakwaters have been employed to shelter fish farms. They are relatively inexpensive, may be moored even in relatively deep water, do not interfere with currents and can be readily modified as farms expand or cages are removed (Kato et al., 1979). Figures 7 and 8 show the use of Bridgestone floating breakwater system to protect fish farms in Japan.

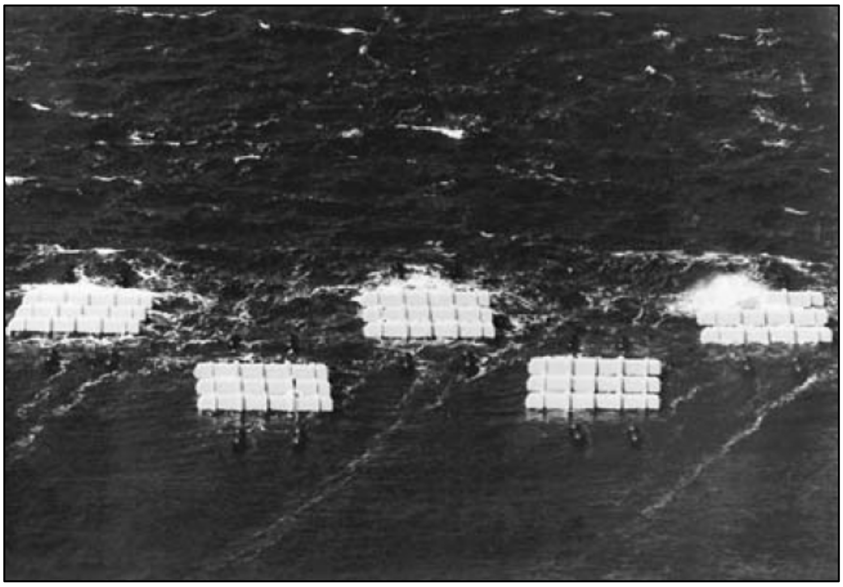

Figure 7: Bridgestone breakwater systems, Japan (Kato et al., 1979)

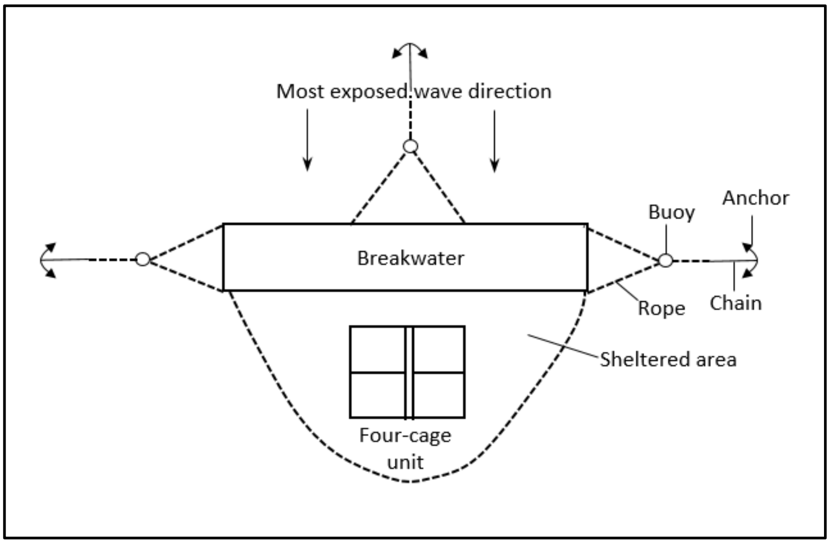

Figure 8: Schematic breakwater deployment for fish farm

3.4 Seabed

The seabed quality in particular affects the mooring system and selection of the anchorage method. A good anchor embeds itself deeply into the seabed. So, it is important to know the sea bottom condition. Not only shells and seagrass on upper layer might prevent an anchor from taking hold but bottom layers with sand, mud, peat or clay require different anchoring characteristics (Cardia and Lovatelli, 2016). Apart from these, the seabed might have the presence of submarine fibre optic cables, telephone lines or pipelines, explosive areas, or historical shipwreck sites (Cardia and Lovatelli, 2016). These limitations should be indicated and considered for cage designs.

Detailed seabed analysis is needed for determining what kind of anchorage method would be suitable for the site. For example, traditional anchorage (gravity method, see Fig. 9) is suitable at sites where there is adequate deep sediment layer (Kankainen and Mikalsen, 2014). If the sea bottom is rocky, drilling would be a better method to keep the mooring system at the site. Echo sounding and sea bottom samples are methods used to evaluate anchorage (Kankainen and Mikalsen, 2014). Seismic survey also be used for seabed soil investigation.

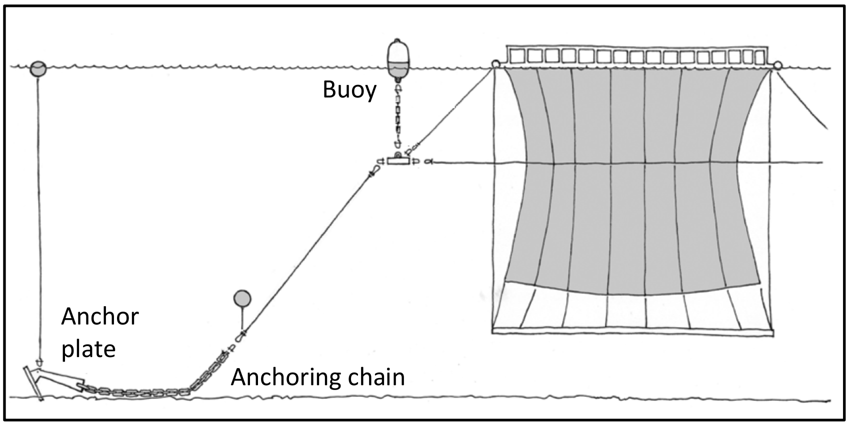

Figure 9: Schematic drawing of components of anchoring and mooring system (Cardia and Lovatelli, 2016)

3.5 Accidental Storm Incidence

Storms (hurricanes, or cyclones or typhoons) are meteorological phenomena that post a risk to offshore fish farms due to associated strong winds, resultant waves and currents generated (Tidwell, 2012; Beveridge, 2004; Kapetsky et al., 2013; Kankainen and Mikalsen, 2014). They mostly occur in the tropical-equatorial zones, i.e. in the area between the Tropic of Cancer and the Tropic of Capricorn, but their incidence can extend to the North Atlantic and North Pacific (Cardia and Lovatelli, 2016).

The occurrence of storms should be rigorously analysed so as to detect an appropriate offshore fish farming site and to predict the environmental forces for cage designs (Huguenin, 1997; Cardia and Lovatelli, 2016). Submersible cages are more suitable for the areas where there is a high incidence of storms and extreme weather conditions (Cardia and Lovatelli, 2016) since wave forces and the pitching motion during storms reduce significantly with increasing water depth. Therefore, the submergibility of offshore cages provides an excellent protection for cages and fishes against the destructive storm incidence.

3.6 Conducive Environment for Fish Welfare

Fish demands the best environmental condition for growth. The best quality of water for fish farming is species-dependent since each type of fish thrives in a particular water temperature, salinity, dissolved oxygen, pH and turbidity (Pillay, 2004). The optimal levels of these parameters are neither known for many fish species nor many things associated with the design of the cage (Shainee et al., 2013). However, the environmental conditions of the selected site indicate the forces that can influence the fish welfare and the integrity of the cage system. Hence, cage designs must not only be robust enough to survive the strong environmental forces, but they should have the means to avoid or dissipate the excess energy in order to provide a stable and relatively quiet environment for the fish to grow. Therefore, the challenge is to design a system that copes best with the environmental forces by means of advanced technology and economically affordable methods (Shainee et al., 2013).

3.7 Infrastructure and Economic Sustainability

Fish farming have to cater for all stages of production from spawning, rearing fries and fingerlings, producing mature fish, harvesting and packing. The distance between the farm site and required land supporting facilities directly affect running costs (Cardia and Lovatelli, 2016). Therefore, Kapetsky et al. (2013) considered 25 nautical miles as the limit for economical offshore site development. Aquaculture Forum Bremerhaven reported the urgent need to plan for a more comprehensive development of land- and water-based infrastructure (Rosenthal et al., 2012; Kapestsky et al., 2013). Water-based infrastructure can offer more opportunities to bring more projects for offshore fish farming by reducing the reliance of land-based supporting facilities.

California Environmental Associates presented the global review of offshore finfish aquaculture in 2018. In the report, it is highlighted that small-scale offshore farming projects will have a challenging time to become a profitable operation. As it is, these small-scale offshore projects have high capital costs, to contend with intense oceanographic conditions, and have an unclear path to economies of scale. Although massive industrialization and automation could provide a more profitable business model, the current offshore farming projects have yet to prove their economic sustainability (CEA, 2018)

4. TYPES OF FISH CAGE DESIGNS

There have been some attempts to classify fish cages by the maritime classification societies (DNV GL, 2017; ABS, 2018; Ng and Jiang, 2019). The attempts are similar to what they applied for the offshore oil and gas industry and hence it is not so appropriate for fish cages. Therefore, we propose a method based on Scott and Muir (2000) categorization of cage designs by nature of structures used for supporting the holding net and Tidwell (2012) categorization by using cage containment methods. In view of these, fish cages may be divided into open net cage system and closed containment tank system. The open net cage system may be further categorized into 5 types as shown below:

I. ***Open net cage system***
   (1) floating flexible cage
   (2) floating rigid cage,
   (3) semi-submersible flexible cage,
   (4) semi-submersible rigid cage and
   (5) submerged cage

II. ***Closed containment tank system***

I. Open net cage system

The open net cage system is the most widely used for marine fish farming. Conventional net-based cages are slender structures, with a low mas compared to the size of the structure. They have a large damping to mass ratio, and this effectively eliminates most resonance problems. Together with their ability to be either deformable (flexible type) or robust (rigid type), the net-based cages make them able to operate in more energetic sea states. In Norway, the open net system is already used in sites with 2m to 3m significant wave heights at 50-year return period which is corresponding to NS 9415(2009) wave class *D – High exposure* (Lader et al., 2017a). Below, various types of open net cage system are described.

4.1 Floating flexible cage

Flexible collar cages were first invented in the 1970s and are now widely used in Japan, Western Europe, North America, South America, New Zealand, Australia. High-density polyethylene (HDPE) is commonly used for the material in modern industrial fish farming. The main structural elements of these cages are the floatable pipes, which can be assembled in various ways to produce the floating collar. The pipes are held together by a series of brackets with stanchions and distributed throughout the entire boundaries to suspend the fish net (Cardia and Lovatelli, 2016).

Advantage: Floating flexible cages have a high resilience to wave forces with a long service life (>10 years) in general (Scott and Muir, 2000). HDPE materials can deform and reduce incident wave forces on the structure and dissipate the wave energy. In addition to this, HDPE has a high resistance to rotting, weathering and biofouling and it can be easily formed into various configurations and relatively cheap when ordered in large volumes (Beveridge, 2004). Moreover, the cage can be easily constructed in-land and towed by boats to install (Cardia and Lovatelli, 2016).

Disadvantage: Floating flexible cages have problems with deformation of the net due strong waves and currents, stanchions that may cause twisting and turning problems, limited walkway access that put workers in harm's way during bad weather, difficulty in placing feed systems due to space constraint and the need for large service vessels (Scott and Muir, 2000).

Examples of floating flexible cages are PolarCirkel a plastic cage concept invented in Norway in 1974 are mostly circular cages with circumference of 60m to 240m (Fig. 10a); and Triton cages developed by FusionMarine covering pen size up to 180m circumference (Fig. 10b).

(a) PolarCirkel HDPE Circular cage <https://www.akvagroup.com/pen-based-aquaculture/pens-nets/plastic-pens>

(b) Triton HDPE Circular cage <https://fusionmarine.com/category/triton/>

Figure 10: Floating flexible cages

4.2 **Floating rigid cage**

Floating rigid cages with robust frame structures (for strength, stiffness, stability and buoyancy) take a different design concept from that of floating flexible cages. Rather than attempting to be wave compliant, these rigid cages are designed to withstand large wave actions. They are generally large structures, constructed from steel, and incorporate a variety of management-related features, such as feed stores, harvest cranes and fuel stores.

The advantages of floating rigid cages are (Scott and Muir, 2000)

- their stable working platform for all husbandry and management operations,
- potential for integral feeding and harvesting systems, and
- construction and repair facilities may be done in conventional shipyards.

while their disadvantages are

- the need for large and heavy structures,
- good port facilities and/or expensive towing to install,
- their susceptibility to structural failure in extreme conditions,
- their large masses require heavier mooring systems, and
- they involve relatively high capital costs

Examples of floating rigid cages are, Havfarm (Fig. 11a and 11b), Pisbarca (Fig. 12), and Seacon (Fig. 13).

- Havfarm has 430 m in length and 54 m wide and capacity to contain 10,000 tons of salmon (over 2 million fish). The Havfarm will be constructed as a steel frame for 6 cages measuring 50m x 50m on the surface, with open nets at 60 m depth. The facilities will be able to withstand 10 m significant wave height (Ship Technology, 18 December 2018).
- The Pisbarca was built by a Spanish company. It is a hexagonal steel structure with 7 cages, with a total volume of 10,000 m^3 and it has a production capacity of 200 tons of fish per annum (Scott and Muir, 2000).
- Seacon, built by Spain in 1987, consists of a hexagonal submerged pontoon construction and a deck construction in light-weight aggregate concrete. It have separated steel tube columns and pretensioned diagonal and vertical struts between top and bottom columns (Bjeske, 1990).

Figure 11a : Havfarm
< https://www.nskshipdesign.com/designs/aquaculture/fish-farm-2/fish-farm/ >

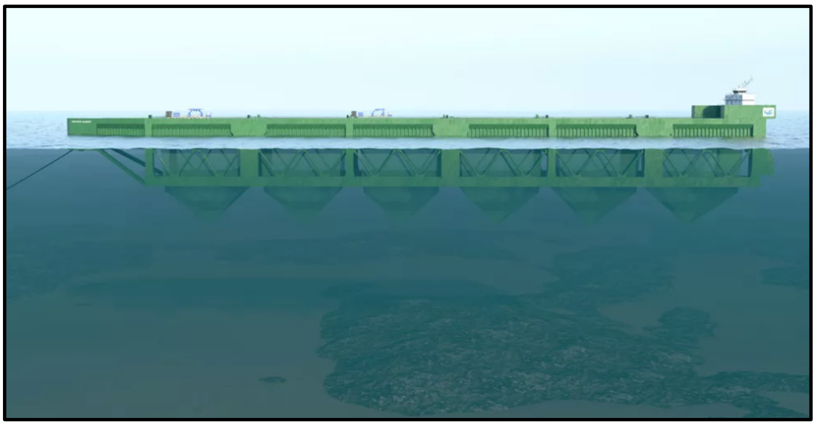

Figure 11b : Havfarm
< https://www.nskshipdesign.com/designs/aquaculture/fish-farm-2/fish-farm/ >

Figure 12: Pisbarca
< https://www.pinterest.co.uk/pin/57772807700395421/?lp=true >

Figure 13: SEACON
< https://www.lightcem.co.uk/fish-farm-c1gnk >

4.3 Semi-Submersible flexible cage

Semi-submersible cages can be characterized by their capability to be submerged from surface waters during a stormy weather to avoid the higher energy regimes. Depending on mechanical types, semi-submersible cage may be divided into two structural classes: flexible and rigid. Tension Leg Cage (TLC) is the one of the representative types of semi-submersible flexible cage. The TLC-submersible design, in which a buoyancy plastic-supporting frame is held in place by vertical mooring ropes attached to concrete blocks on the seabed and to sub-surface buoys. In storms or strong currents, the cage responds naturally where the net is being pulled under the water and thus escaping the worst wave action (Scott and Muir, 2000; Beveridge, 2004).

Advantages: TLC cages are lighter and simpler structures. They do not have any metal structural components in their designs. Therefore, the cages are relatively inexpensive. They are pulled under the water by strong currents during storms so that they are far less exposed and subjected to less physical stress. The reduced movement could also potentially reduce fish injuries and fracture of structures. They can be combined with conventional floating flexible cage by adding an upper cone and tension leg mooring. The upper cone can be removed and the cage raised for harvesting and net changing (Scott and Muir, 2000).

Disadvantages: TLC cages need sub-surface feeding systems. Mooring strength is critical and the heavy block anchors used are difficult to install. Cage volume reduction due to submergence of cage for a long period of time may affect fish's welfare (Beveridge, 2004). Tension leg mooring system will behave more like a fixed structure and wave forces are directly countered by the tendon stiffness forces, thereby a large volume with high mass cage may not be suitable due to vulnerability of mooring lines (DNV GL, 2010).

An example is the Refa tension leg cage design concept as shown in Fig. 14. The cage is available in a variety of sizes up to 12,000 m^3. The maximum harvest biomass is about 300 ton based on 25kg/m^3 stock density. The cages have been deployed in Italy, Spain, Portugal and Brazil.

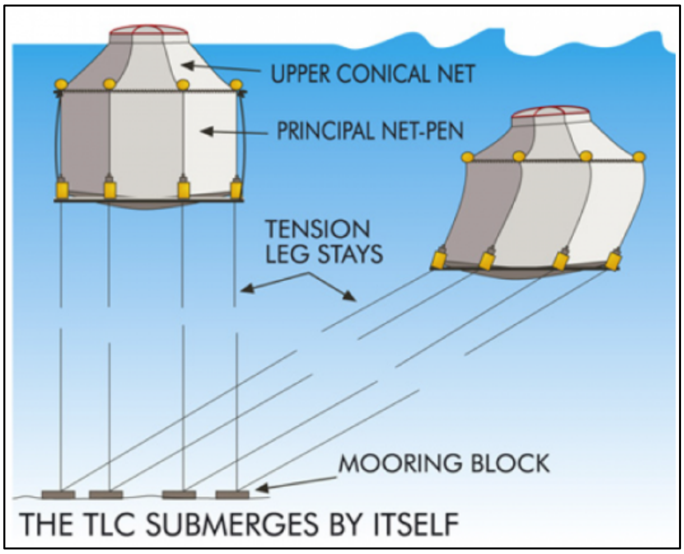

Figure 14: Refa tension leg cage concept design
< http://refamed.com/gabbie_mare/tlc_system.html >

4.4 Semi-submersible rigid cage

Semi-submersible rigid cages are designed with rigid framework elements restricting movement or volume change in response to external wave and current forces. Normally having steel frame structures, the cages have adjustable ballast tanks to raise or lower the system. With a more rigid structure, it allows to have service facilities such as self-contained feeder systems (Scott and Muir, 2000).

Advantages: Semi-submersible rigid cages may provide the longest service life as proven by similar designs operated by the oil and gas industry. The system is able to equip integrating feeding systems, harvest cranes and surveillance systems. With a rigid frame, the cages maintain their volumes and keep fish in place (Scott and Muir, 2000). A semi-submersible body has relatively small vertical motions because of its relatively large mass and a low centre of gravity. Thus, it can be designed with a large natural period to avoid wave resonance effect (DNV GL, 2010). In addition, it is able to protect facility by submerging the fish cages that results in less wave excitation forces.

Disadvantages: Semi-submersible rigid cages have a high capital cost since they are large and complex steel structures that require rigorous engineering analyses, design and high-quality control in construction to ensure safety in offshore operation. When the cages are in a submerged mode, there is poor access for harvesting, difficulty for changing or cleaning nets, limited work surface poses an adverse effect on operation.

Examples of semi-submersible rigid cages are Ocean Farm 1, Shenlan 1, Shenlan 2, Viewpoint Seafarm, Spider Cage, SSFF150 Pen, and Keppel offshore rig fish farm.

Ocean Farm 1 (Fig. 15) was developed in Norway and built in China. Ocean Farm 1 is a result of robust technology and principles used in submersible offshore units. With diameter of 110m and volume of 250,000 m^3, the cage is able to accommodate 1.5 million salmons (Zhao et al., 2019). It is intended for offshore installation in water at 100 to 300 meters in depth with 25year lifespan. It has more than 20,000 sensors and over 100 monitors and control units.

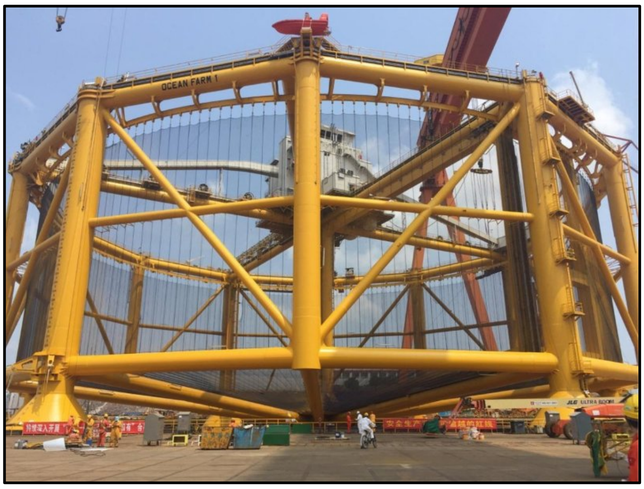

Figure 15: Ocean Farm 1 (Picture courtesy of Charles Lim)

Shenlan1 and Shenlan 2 were developed for salmon farming about 130 nautical miles off the shore of Rizhao in east China’s Shandong province. Shenlan 1 has already been deployed at the site and it has a diameter of 60m and 35m in height that is able to culture 300,000 salmons (Fig. 16a). Shenlan 2 is in the planning stage. It will have a 60m diameter and a height of 80m and it can accommodate about 1 million salmons (Fig. 16b).

(a) Shenlan 1

(b) Shenlan 2

Figure 16
< http://www.ccccisc.com/en/haiyanggongchengxiangguan/70.html >
< http://www.ccccisc.com/en/haiyanggongchengxiangguan/72.html >

Nova Sea AS, a Norwegian company, designed two innovative concepts of Viewpoint Seafarm (see Fig. 17) and Spider Cage (see Fig. 18) for offshore fish farm solutions based on semisubmersible technology. Viewpoint Seafarm comprises a hub, which is supporting four floating net cages interconnected through a dedicated hinge system. Each floater has a projected area 50m x 35m. A scale testing has been done with 11m significant wave height and the system showed stable motion response (Lindeboom, 2018). The Spider Cage has a dedicated barrier, with a diameter of 100m having an outer steel ring with another ring inside with a heave compensation. It is designed to shield the actual fish cage from heavy sea conditions and sea lice. The design has been tested up to sea states of 11m with and without current, where general motions, accelerations, loads and sloshing have been accessed (Lindeboom, 2018).

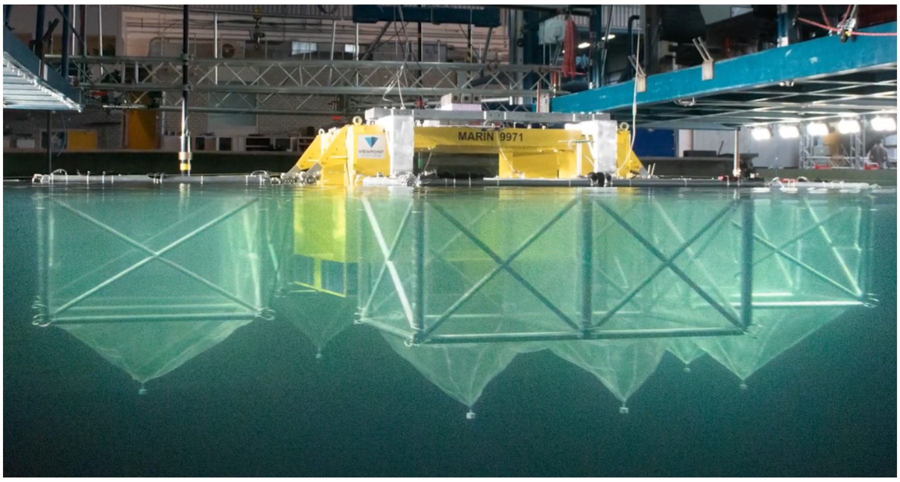

Figure 17: Viewpoint Seafarm
< https://www.youtube.com/embed/WWiU0dm-iKQ?autoplay=1&modestbranding=1&rel=0&showinfo=0&vd=hd1080 >

Figure 18: Spider cage
<https://www.youtube.com/embed/gpPfUwD0te0?autoplay=1&modestbranding=1&rel=0&showinfo=0&vd=hd1080 >

De Maas SMC, a firm operating in the offshore oil and gas services industry, is partner in a $151million local Chinese government to build a deep-water aquaculture farm off the coast of China. De Maas will design and build five SSFF150 pens (Semi-submersible Spar Fish Farm) each 139m in diameter and 12m high (see Fig. 19). The central tower will house machinery spaces, feed storage and provides accommodation for operators. By submerging underwater, the pen is able to be protected from storms.

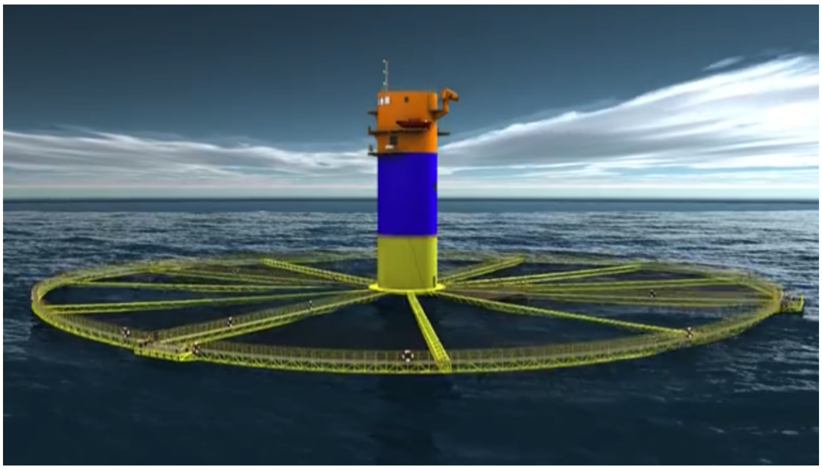

Figure 19: De Maas SSFF150 pen
< http://www.demaas-smc.com/ >

The prototype offshore rig concept cage developed by Keppel in Singapore (see Fig. 20) comprises a semi-submersible — a raised platform above sea level connected to a floating ring pontoon by columns — attached to six hexagonal fish cages. The cages are submerged underwater to minimise sea surface obstruction. The cages are controlled remotely and can be raised above the sea level to harvest fish or for maintenance or repair. A platform above water can house hatcheries to supply fish fry.

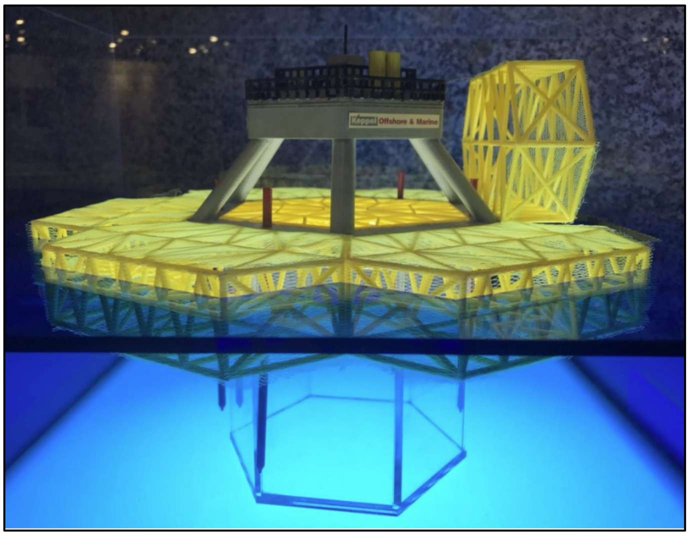

Figure 20: Keppel offshore rig for fish farm
< https://www.todayonline.com/singapore/offshore-rigs-fish-farms-beingdeveloped-keppel >

4.5 Submerged cage

Finnmark Research Centre, Hammerfest, Norway carried out a pilot study with Atlantic salmon in a submerged cage in 1992. 100 salmons were kept submerged in a 600 m^3 closed cage to a depth of 20-26m for 42 days. During this period, swimming behaviour appeared normal and all the fish survived (Reinertsen, 1993; Dempster et al. 2008). Unless submerged condition for long periods does not give negative impacts on fish's well-being, the best way to avoid the worst effects of severe surface conditions would be to use fully submerged cages.

The distinct difference between a semi-submersible cage and a submerged cage is the definition of primary mode for normal operating condition. For the former, the primary mode is on the surface whereas for the latter the primary mode is in a submerged position (Scott and Muir, 2000). Normal operating condition of submerged cages would be at a suitable water depth below from the hazardous upper water column. The systems could be raised temporarily to the surface for necessary maintenance requirements and for fish harvesting. Various designs have been proposed and some pilot scale or commercial systems have been built.

Advantages: The submerged cage system could either be unattended by surface units, accessed only when needed, or remotely controlled. Submerged cages have the best features to avoid surface debris and effects of storms (Scott and Muir, 2000). Its structural strength does not need to be as great as surface structures.

Disadvantages: The submerged cage system has a lack of visibility in normal operation, relatively complex to operate due to its submerged mode and maintenance and operating services are difficult. Therefore, their operating costs may be relatively higher than surface mode structures.

Examples of submerged rigid cage designs are Sadco (see Fig. 21), AquaPod (see Fig. 22) and NSENGI sinking fish cages (see Fig.23). Sadco is a Russian design that has been evolving since the early 1980s (Bugrov, 2006). A ballasted upper steel hexagonal superstructure carries the net which is kept in shape by a lower sinker tube. The cage volumes are available up to

2000 m^3. AquaPod was developed by Ocean Farm Technologies in the United States. It has a two-point anchor for mooring and some operational advances such as net cleaning and removal of mortalities. NSENGI (Nippon Steel & Sumikin Engineering Co., Ltd) had carried out offshore verification testing of large scale sinking cages at a salmon farm which is 3 km from shoreline of Sakaiminato, Tottori Prefecture, Japan. Each cage has a volume of 50,000 m^3 with wave and current resistance of 7m and 2knots, respectively. The cages are serviced by a jack-up platform that houses the equipment and feedstock storage facility for automated feeding of the fish (see Fig. 23).

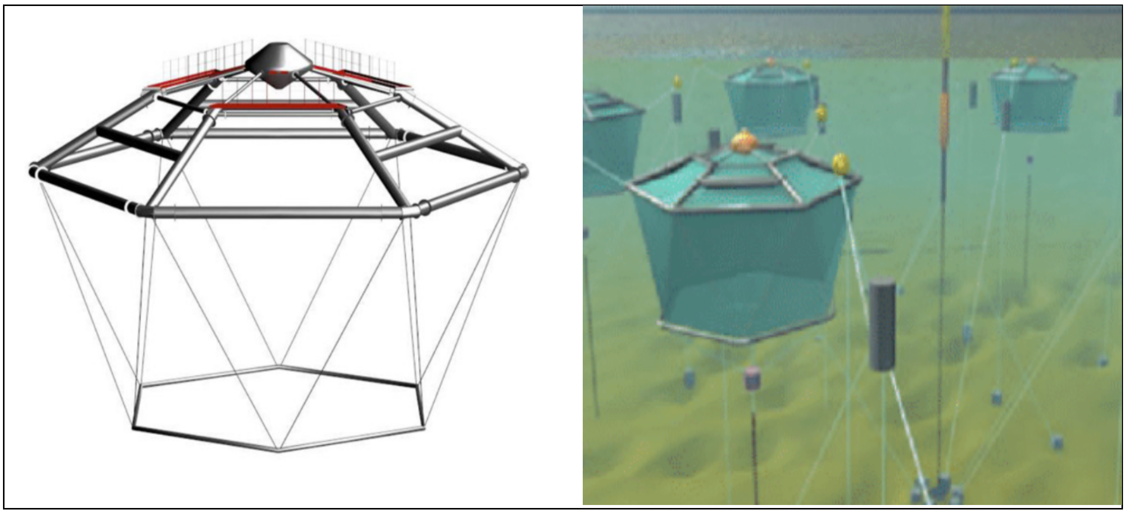

Figure 21: Sadco submerged rigid cage < http://www.sadco-shelf.com/ >

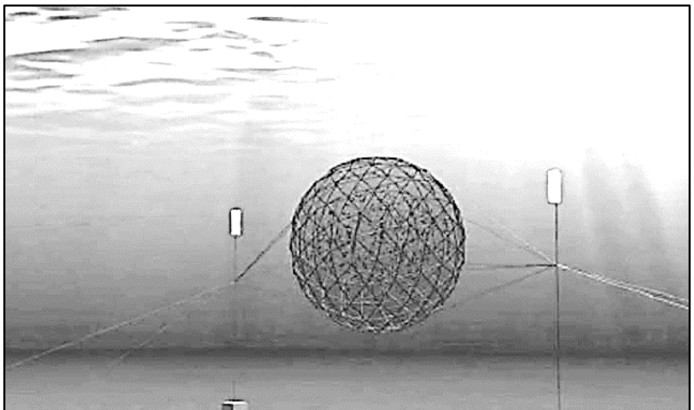

Figure 22: Submerged AquaPod cage from Ocean Farm Technologies (Tidwell, 2012)

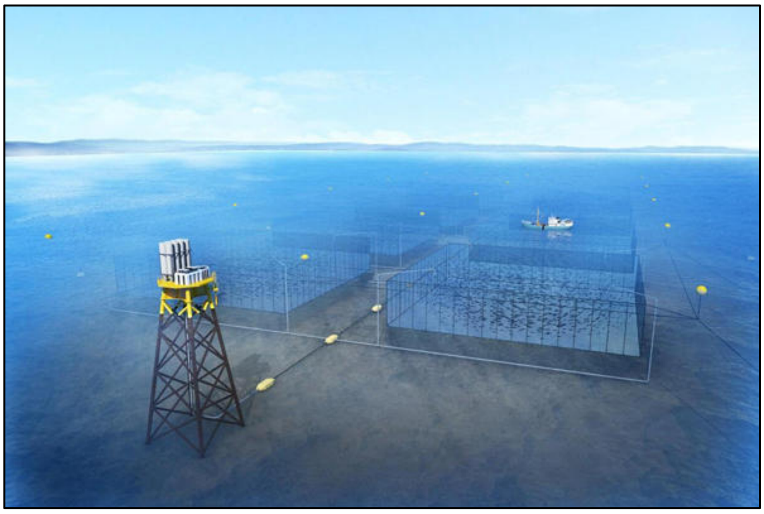

Figure 23: Sinking fish cages

< https://www.eng.nipponsteel.com/english/news/2016/20161003.html >

II. Closed containment tank system

In order to control the water quality and the production process, closed containment fish tanks have been introduced in the 1990s (Beveridge, 2004). This closed containment fish tanks are generally sited on land and they involve recirculation system for the water (Tidwell, 2012).

Floating closed containment tanks for offshore fish farming are very recent developments prompted by the need to protect the fish from sea lice and other parasites. Floating closed containment tanks contain water that is constantly refreshed by a flow through system which also helps to provide proper temperature, sufficient oxygen and waste removal.

Advantages: By having control over water replacement, the water can be constantly disinfected to remove pathogenic organisms. External environmental events like algae bloom is no longer a problem (Chadwick et al., 2010). Organic wastes can be removed by biofiltration system before discharging the water back to the sea. The threat of predators (such as sharks and seals) is completely eliminated. It also can achive a higher production rate when it compared to the open cage system (Tidwell, 2012). This is due to the greater control and inputs into these systems and the fact that their physical parameters can be optimized for maximum productivity.

Disadvantages: Floating closed rigid containment tanks require a power supply system when they are deployed in offshore sites. It would be too expensive to bring power from land for offshore fish farming operation. In addition, the system requires significant construction and equipment costs, more management demands for monitoring and intervention, and detrimental sloshing effect to both structure and fish by the contained water.

An example of floating closed containment type is the fish farm egg (see Figs. 24a and 24b), developed by "Hauge Aqua" using a fully enclosed egg-shaped structure. The water flow enables the system to draw inlet water segregated from where outlet water is released. Water enters by the use of two main pumps that suck water from 20m below the water surface. The water quality and volume can be controlled, ensuring steady oxygen levels. It is estimated to cost about NOK 600 million (about USD 60 million).

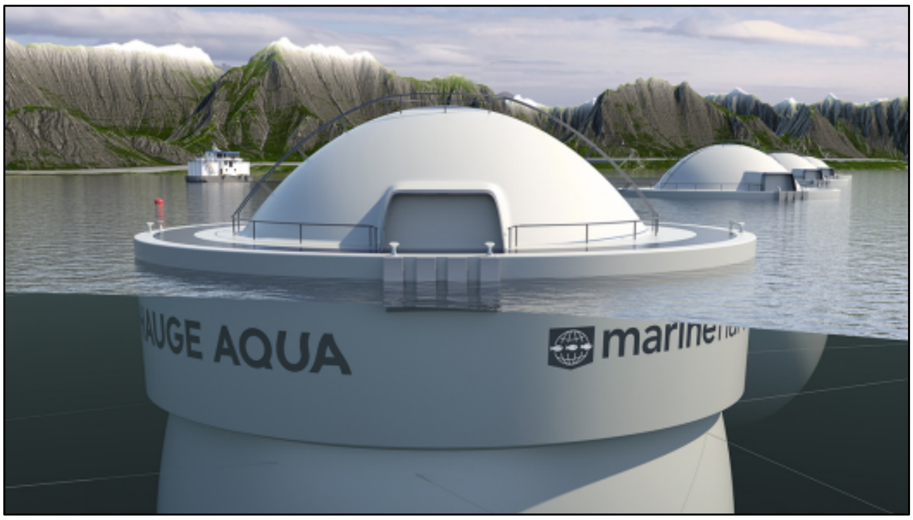

Figure 24a: Closed fish farm concept "fish farm egg"
< http://sysla.no/fisk/skal-bruke-600-mill-pa-lukkedeoppdrettsegg/ >

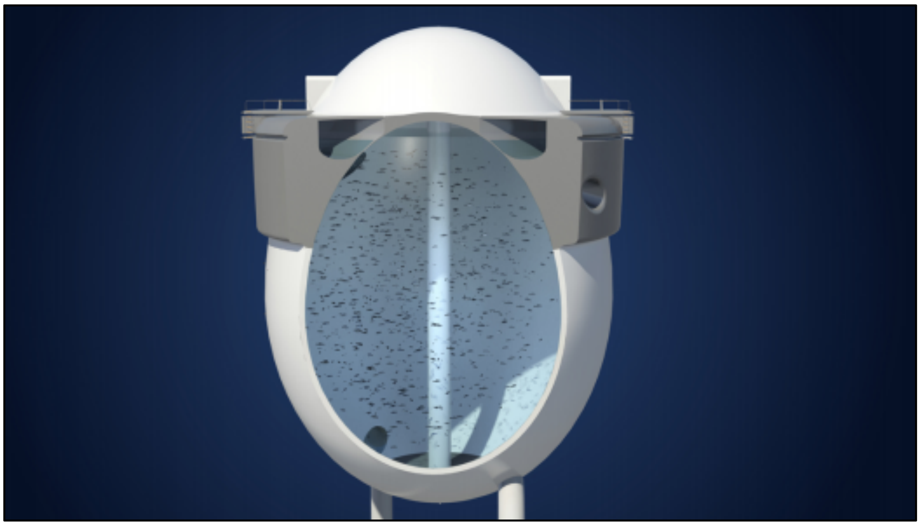

Figure 24b: Closed fish farm concept "fish farm egg"
< http://sysla.no/fisk/skal-bruke-600-mill-pa-lukkedeoppdrettsegg/ >

Marine Harvest ASA, the world's biggest Atlantic salmon producer, proposed farming salmon inside an unwanted container ship (McFerron, 2016). Container ships have a number of watertight holds that are able to contain fish inside and the top hatch covers protect fishes when they are closed (see Fig. 25). The on-board facilities such as water pumps and power supply can be used for fish farming. Finnegan (2016) estimated the cost for adding tanks and adjusting pumps to make them operable for a salmon farm to be about USD 2.5 million to USD 5 million which is rather cheaper than the cost for 2-3 years in sailing empty ships for general maintenance, hiring a skeleton crew, and keeping them in port.

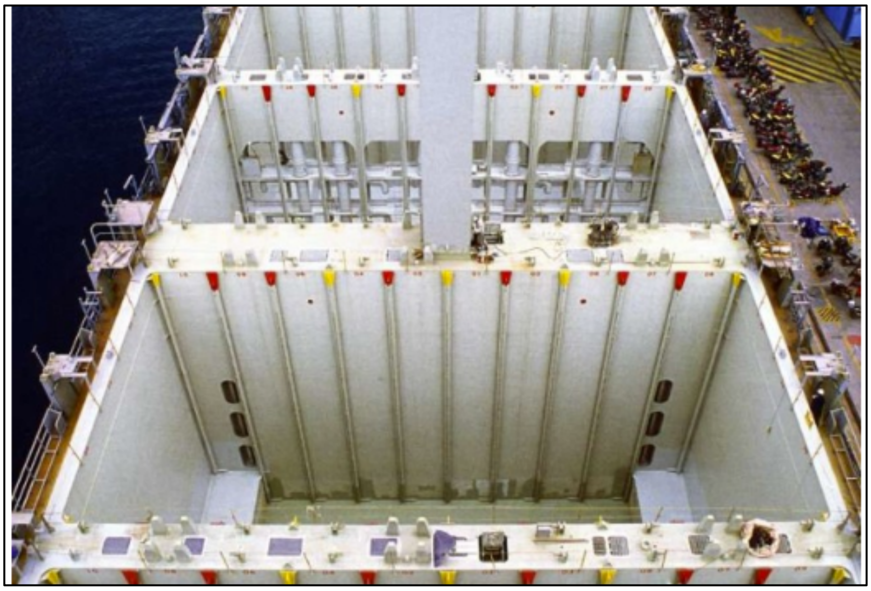

Figure 25: Use a ship as a salmon farm (Finnegan, 2016)

Neptun developed by Aquafarm Equipment (Fig. 26a). The tank has an internal diameter of 40m, a circumference of 126m, a depth of 22m and the gross volume is 21,000m^3. Figure 26b shows an internal view of the tank with inlet and outlet holes for water circulation. The tank is made from Glass Fibre Reinforced Polymers (GFRP) elements and reinforced with steel in areas that bear the most stress. The design also includes a pump system to extract large volumes of water from a depth of 25m or more. As the concept of the containment tank is to collect the waste from the fish and uneaten fish feed from the sloped bottom, there is a flexible pipeline that connects the low point to the waste separator.

Figure 26a: Neptun closed containment fish tank
< http://aquafarm.no/closed-cage/ >

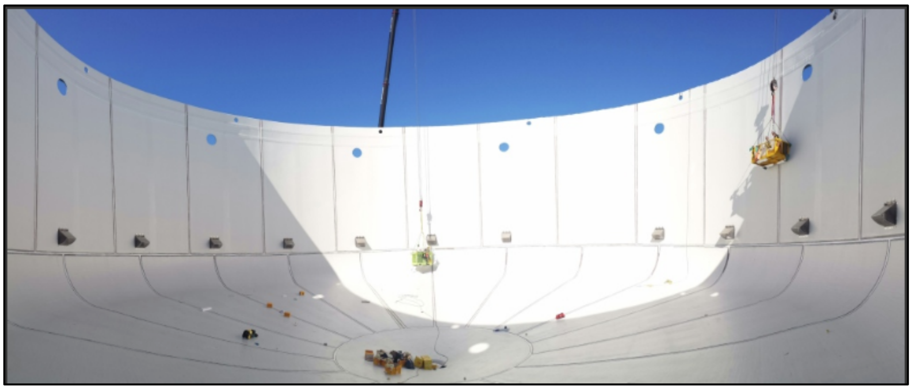

Figure 26b: Internal view of Neptun semi-closed containment fish tank
< http://aquafarm.no/closed-cage/ >

Dr. Techn. Olav Olsen, Norway based marine technology consulting company, proposed a closed containment tank by using concrete material for offshore farming (see Figs. 27a and 27b). The cylindrical concrete tank has a 14.8m inner diameter, 16.5m outer diameter and 6m height. Its bottom has a sloping bottom for easy collection of organic waste (Olsen, 2019).

Figure 27a: Concrete containment fish tank (Picture courtesy of Tor Ole Olsen)

Figure 27b: Concrete containment fish tank on site
(Picture courtesy of Tor Ole Olsen)

AME2 Pte Ltd, Singapore based company, has developed a closed containment flow through floating fish farm called Eco-Ark as shown in Fig. 28a. It has several containment tanks with flow through water supply system. It has a roof equipped with solar panels to supply electricity for the fish farm (Leow, 2019). The Eco-Ark allows augmentation and integration by forming a fleet connected to a lift-dock facility that enables one to cultivate and process massive amount of fish on site (see Fig. 28b). The Eco-Ark was constructed in Batam Island, Indonesia, it will ready for deployment in Singapore waters in September 2019.

Figure 28a: Eco-Ark closed containment system
(Picture courtesy of Mr Ban Tat Leow, the inventor of Eco-Ark)

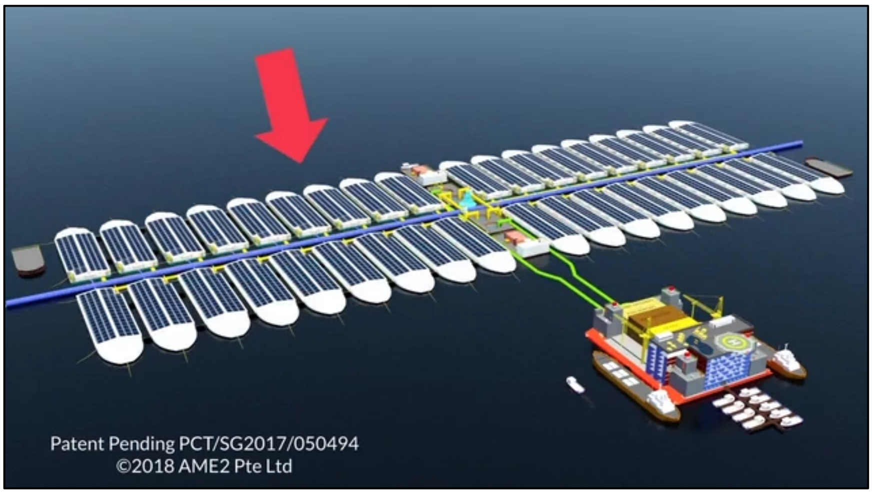

Figure 28b: Eco-Ark fleet connected to lift-dock (Picture courtesy of Mr Ban Tat Leow)

The Norwegian salmon farmer, Marine harvest, developed a closed containment tank design named marine donut (see Fig. 29). The marine donut is able to accommodate 200,000 fish in each unit. In 2019, Norway's directorate of fisheries granted permission for 1,100 tonnes of biomass to be used to test the design.

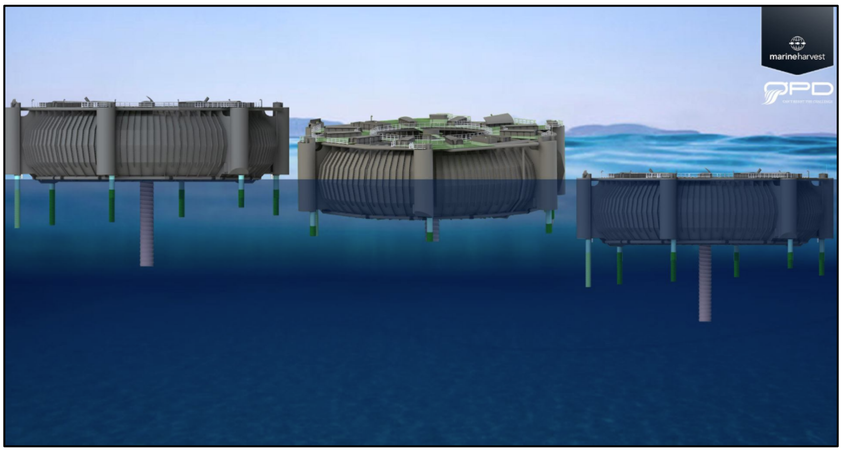

Figure 29: Marine donut – Close containment concept design of Marine harvest
< http://marin.bergen-chamber.no/en/teknologi/Growth-through-innovation/ >

5 Discussion of various cage designs and future of offshore fish farming

Table 3 summarizes the features of aforementioned fish cage designs with respect to their shapes, sizes, volumes, fish stocks, significant wave heights, distances from shorelines and costs. The table is reproduced from the data of Tunner (2000) study and various cage manufacturer's design parameters as mentioned earlier. In the table, it has been assumed that the stock density is 24 kg/m^3 and the weight of a mature fish is 4 kg based on private communication with Tassal of Australia.

Table 3: Classification and features of cage designs

Types of Fish Cages	Material	Shape	Maximum Size	Max. Volume (m^3)	Max. stock Weight (ton)	Max. Number of fish	Significant wave	Distance off-	Capital cost
Floating flexible (*PolarCirkel)*	Flexible hose	Circle	240m in circumference	72,500	1,740	435,000	3.5 ~ 4.5	< 2	Low
Floating rigid (*Havfarm)*	Steel	Ship-like, Hexagon, Square	430m in length	415,000	10,000	2,500,000	10	>2	High
Semi-submersible rigid *(OceanFarm1)*	Steel	Circle, Hexagon	110m in diameter	250,000	6,000	1,500,000	6	>2	High
Semi-submersible flexible (*Refa)*	Tension leg and flexible hose	Circle, Hexagon	28m in diameter	12,000	288	72,000	12	>20	Low
Submerged (*Aquapod)*	Steel, Concrete	Sphere	20m in diameter	4300	103	25,000	15	>20	High
Floating close containment tank (*Neptun)*	GFRP, Steel, Concrete	Barge, bucket	12 m in circumference	21,000	504	126,000	-	-	-

The volumes of floating flexible cages, commonly used in nearshore farming sites, have increased over time to accommodate 435,000 fish in a single cage. Normally, a group of 12 cages can produce up to 5 million fish. Some plastic circular cages have been given an offshore designation, and have hitherto survived storms with significant wave height H_s of 4.5m (Tunner, 2000). However, there is little empirical or theoretical data as yet, to offer complete confirmation of the extreme sea state condition that the flexible circular cages may be expected to survive on a long-term basis. Floating flexible cages have not been deployed in highly exposed sites that are expected to cause a large deformation of the floater, damage of stanchion and connectors, and contraction of net space under severe wave actions.

Floating rigid cages may be deployed at some exposed offshore sites where an occurrence of extreme storms is rare. Semi-submersible rigid cages have become the most popular type due to its submergibility and robust structure against a harsh environmental condition. There have been some projects launched in Norway and China by using semi-submersible platforms for offshore fish farming (e.g. Ocean Farm1 located about 5 km off the coast of central Norway and Shenlan 1&2 located at 240 km from the Rizhao coast, China).

Semi-submersible flexible cages and submerged cages may be deployed at more exposed sites. In general, the volumes of these types of cages are relatively small. There is a size restriction that prevents them from expanding to a large scale that is able to establish a profitable model. This size restriction is due to the difficulty of keeping the cages in tension by using the tension mooring line system in high frequency motion. So far, it is not known if there are any semi-submersible flexible cage and submerged cage being deployed in offshore sites. This may be due to the lack of remote technologies for operating such types of fish cage.

Studies about floating close containment tanks indicated challenges in waves (Lader et al., 2017b). Since the cage is closed, the water inside is forced to move with the cage, and the mass of the enclosed water added in the systems total mass. The increase in mass causes a corresponding increase in the forces associated with the system accelerations. A related consequence of the enclosed water is the potential of sloshing response of the enclosed free surface. In a tank without any internal structures, as is the case for most closed aquaculture cages, very little damping resistance to the sloshing, and therefore large responses may occur if the cage is excited with frequencies close to the natural period. The sloshing motion is potentially bad for the fish welfare, and it can also significantly affect the horizontal plane motion of the whole cage, as well as cause stresses in the cage wall (Kristiansen et al., 2018). Therefore, while a conventional flexible net-based cage has few resonance problems, a closed cage has significant challenges with resonance, especially connected to sloshing.

Although operating costs are varied depending on the types, Bjørndal and Tusvik (2018) estimated the operating costs depend on the farming practices (see Table 4). Approximately 35 NOK (4 USD)/kg may be assumed as the target value to achieve for offshore sites in order to compete against nearshore or on land fish farming costs.

Table 4: Estimates of cost for nearshore fish farming (Bjørndal and Tusvik, 2018)

	NOK/kg
Open cages in the sea	30.6
Containment tanks on land	43.6
100g fish on land, then in open cage in the sea	28~33.8
500g fish on land, then in open cage in the sea	28.9~30.7
1000g fish on land, then in open cage in the sea	30.8~32.4
Closed containment tanks in the sea	37.9

Although there are uncertain risks in fish farming operation in offshore sites, there has been an overwhelming focus to develop offshore fish cage designs with the following stakeholders' demands:

(a) Able to be placed in a high energy offshore environment with optimum farming conditions,
(b) Possess structural integrity and durability over the long period of operation,
(c) Able to secure the welfare of fish and safety of farmers operating in offshore sites,
(d) Large scale production of fish from obvious economic angle

It is possible to find durable and long-term operation offshore structure proven by oil and gas industry structures which can be utilized for fish farms by modifying or repurposing them (e.g Viewpoint Seafarm, see Section. 4.4). However, offshore fish farm structures face more challenges because they have to ensure the welfare of the fish. For example, in an open net system that makes use of offshore oil and gas platforms, there is a restriction on the site selection because it cannot protect the fish from the high energy environment. In order to overcome the restriction, floating breakwaters can provide a solution but its construction cost is high and affects the return of investment. While the closed containment tank design may be a promising solution to protect fish from the high energy environment, the sloshing effect must be addressed.

The CAPEX (Capital expenditures) and OPEX (Operational expenditure) of offshore fish farms are certainly much higher than nearshore fish farms. In order to make it more economically viable, offshore fish farm has to be several times larger than nearshore fish farms so as to reach the economy of scale and a large production of fish. Another way to lower the costs of offshore fish farming is to co-locate offshore renewable energy production plants with the offshore fish farm so as to share the costs of the floating platforms and the mooring systems (Kaiser et al., 2011; Holm et al., 2017). Moreover, the offshore renewable energy facilities can provide the necessary power supply for the fish farms as well as the freshwater via desalination process and oxygen for fish pens via water splitting (Papandroulakis et al., 2017; Wang et al., 2019). The floating platforms will be able to accommodate fish feed silos and equipment so that transportation costs and service vessels for fish feed delivery can be reduced. Figure 30 shows Australia's Blue Economy Cooperative Research Centre idea of an aquaculture farm being co-located with multipurpose platform and offshore renewable energy plants. Interestingly, the co-location of offshore renewable energy facility and water desalination plant with fish farms has recently been implemented by the Guangzhou Institute of Energy Conversion (GIEC). Figure 31 shows GIEC's semi-submersible wave powered aquaculture cage with seawater desalination plant on board and solar panel roof.

Figure 30: Australia's Blue Economy CRC vision of a co-located aquaculture farm, multipurpose floating platform and offshore renewable energy plants (Picture courtesy of A/Prof Irene Penesis of University of Tasmania)

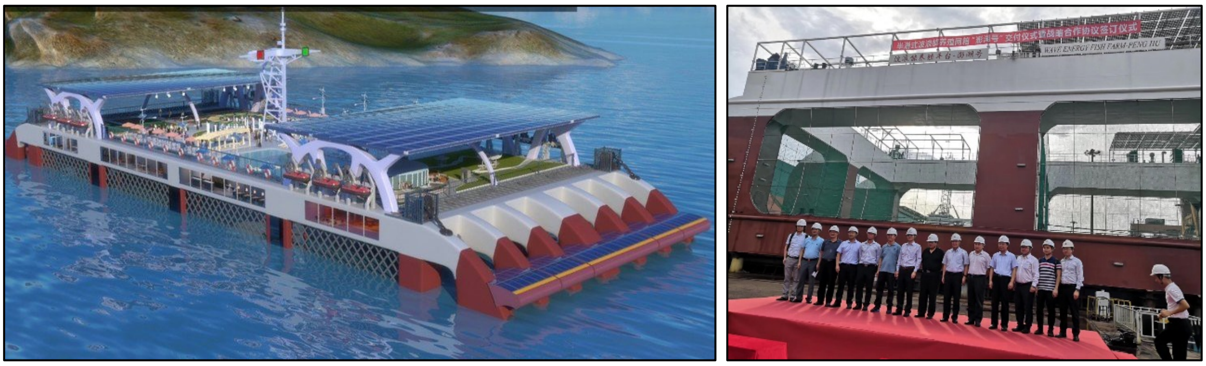

Figure 31: Semi-submersible wave powered aquaculture cage by Guangzhou Institute of Energy Conversion (Picture courtesy of Mr Ban Tat Leow)

6. Concluding remarks

It is inevitable that fish farming has to move offshore for sustainable farming, larger sea space and higher fish production. However, offshore operation generally requires high capital and production costs (Jansen et al., 2016) and therefore rigorous research and development must be carried out urgently to seek cost effective solutions. Also, fish cage designs should consider health of the fish, fish diseases, exposure to toxicity, fish growth, harvesting of fish, transportation to the market and environmental issues. Feasibility of offshore fish farming may be achieved through adoption of new development of multi-functional and autonomous infrastructure that has been validated in oil and offshore industry. By co-locating offshore renewable energy systems (wind turbines, wave energy converters) and floating platforms (that can accommodate fish feed silos, feeding equipment, harvesting cranes and nets, fish processing and packaging plants, waste treatment plant, desalination plant) with offshore fish farms allows one to leverage on the benefits of colocation, vertical integration and shared services and to reduce operating time and cost.

It is hoped that this paper will encourage offshore and marine engineers, structural engineers, naval architects, fish scientists, energy systems experts, material scientists, fish farm operators and offshore renewable energy companies to come together to work on solving the challenging problems faced by offshore fish farming.

Acknowledgements

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