OS Aqua

Open Sea Aquaculture in the Eastern Mediterranean

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Executive Summary

This report examines technological options for an open sea aquaculture station in the Eastern Mediterranean, which is one of the WP5: "Design of offshore marine aquaculture station" objectives that aims to suggest suitable cage options for an open sea aquaculture site in Cyprus.. For the completion of this study an extensive search of the technologies used in open sea aquaculture yield thirty-three designs. These were considered for their use in the area and seventeen cage designs were further studied in this report. To collect additional information the team interviewed representatives of four companies (Kimagro, Bandinotti, Gili-Ocean and Innovasea). Information also fed the design of a new engineering approach to open sea aquaculture. The design of the station depends on many factors, with the most important ones being the location, depth, size, and weather conditions of the areas of installation. The location depends on the possible conflict with other activities that include shipping routes or tourist areas, while proximity to tourist areas relates to the aesthetic aspect of the station. The depth affects mooring considerations that are a major factor determining the design of the station and the cost. The size of the area is an essential aspect that helps assess the number and size of cages, which are directly linked to yield and financial sustainability. Finally, weather conditions determine the type of aquaculture station design. This report takes input from other work packages on wave heights and information on past harsh weather conditions based on areas of depths between 100m-200m that allow the placement of cages with less conflict with other activities. The locations and weather data were made available to technology providers and marine engineers to determine the feasibility of utilizing existing or influencing new designs. Based on a survey of existing aquacultural open sea facilities, it was determined that some technologies are suitable for Cyprus, although not recommended for more than 80m depth, while others require a large investment. The report also presents an alternative concept that combines the rigid structure of larger investment designs to sustain harsh weather, scaled down to the financial resources and available shipyard facilities of Eastern Mediterranean countries. As the new proposed design is based on the constraints and characteristics of the local environment, it is not assumed to be universally optimal. However, the technology can be applied to other environments at a global level where the size of the countries involved and the local environment are similar to the Eastern Mediterranean region. Taking this into consideration the study concluded that the Badinotti, Innovasea, new OS-Aqua design and traditional cages could be used for further investigation for their use in an open sea aquaculture site in Cyprus.

Contents

1 Introduction

In this deliverable, a survey of existing open sea aquaculture technologies was conducted with input taken from the available literature and stakeholder engagement. The survey focuses on the most relevant technologies, either due to their possible applicability to the local environment or to draw insights for the design of the new open sea aquacultural station. The goal was to identify types of technologies that are suitable for the scope of this project and then identify two or three indicative examples of technologies that will be suggested for use in the financial analysis of WP7: "Financial and Legal Frameworks." Although the focus is on technologies that are suitable to the Mediterranean and for depths ranging between 100 m and 200 m, solutions that are too costly for the size of Cyprus and Eastern Mediterranean countries are still provided for reference and comparison. The solutions represent a significant upgrade to current practice that is projected to attract interest and investment without a prohibitive increase in development and operational expenses that actors in the Mediterranean region will not be prepared to adopt. The solutions are to be further studied, and the selection will be refined based on financial and environmental factors considering calculations of yield and modeling of environmental carrying capacity performed in WP3.

With the goal to identify technologies and refine a selection of technologies that are suitable for the area, the consortium has consulted stakeholders through a stakeholder engagement process conducted in WP2: "Dissemination Activities", in which technology providers discussed available solutions with the consortium. The process of technology selection was run together with the selection of candidate areas identified in WP4: "Spatial Planning for Marine Aquaculture". The application of the technologies selected with their details of mooring, size, and yield were matched with the candidate areas. This effort started to complete the information gathering and initial decision phase required to build financial scenarios.

The deliverable also utilizes the survey from literature and commercial sources to inform the concept of a new design of open sea aquaculture suitable for the Eastern Mediterranean. By distilling present knowledge and combining it with the requirements, capacities, and infrastructure of the local market, the present deliverable suggests a new design for offshore aquaculture technology.

The methodology and organization of the document are as follows. A review of existing technologies related mostly to cage design is first provided. The cage designs are assessed based on their suitability for Cyprus and Eastern Mediterranean countries regarding installation, operation, and maintenance costs. The cage design ideas and type are used to decide on the concept of a new design that is possible to construct in Cyprus shipyards. A refined selection of aquaculture facilities and the new aquaculture facility design is then provided as input for other work packages dealing with sensing and monitoring of the cage, mooring, and environment as well as the financial aspects of the project.

2 Survey of existing open sea aquacultural technologies

Existing technologies related to cages, mooring, feeding, and automatization methods are listed in this section. This survey is used to refine the selection of technologies that apply to the Eastern Mediterranean, which are further investigated in the following sections. A survey from the literature on aquaculture cage technologies, equipment, mooring systems, and emerging techniques is first provided, followed by a survey of specific systems provided by relevant companies.

2.1 Aquaculture technologies

2.1.1 Classification of aquaculture enclosures (cages or pens)

Aquaculture enclosures are designed based on their location, operation, environment, and structure (Costa-Pierce and Bridger, 2002). The different types of cages include surface-oriented, anchor-tensioned, self-tensioned, semi-rigid submersible, and barge-type. Moreover, cages are floating, submerged, or submersible. Cages can also be rigid or flexible. (Beveridge, 2008; Huguenin, 1997) and can be made with different materials. Aquaculture cages are categorized as either an open net cage or a closed containment tank system Chu et al. (2020).

a. Open net cage categories:

- Floating flexible cage, i.e., Dunlop, Bridgestone, (Gunnarsson, 1988; Brittain, 1996; in Scott and Muir, 2000; Cardia and Lovatelli, 2016; He et al., 2018; Mohapatra and Soares, 2019)
- floating rigid cage, ie., Havfarm (Li et al., 2019; Huang et al., 2020), Pisbarca and Seacon (Loverich, GF, Gace, L. 1997. Scott and Muir, 2000)
- Semi-submersible and submersible flexible cage, i.e., Refa, The Oceanis cages to Badinotti, GiliOcean station can also be submerged (Chambers and Howell, 2006; Dempster et al., 2008; Korsøen et al., 2009, Benetti et al., 2010; Langan et al. 2012; Lin Li et al. 2017)
- Semi-submersible rigid Farmocean's Ocean Farm 1 Shenlan 1, Shenlan 2 on and submerged cage rigid, i.e., Aquapod, KZO Sea Farms Sadco, Trident, Sea Trek (Brenden et al., 1999; Scott and Muir, 2000; Helsley & Kim, 2005; Chu et al., 2020; Cardia and Lovatelli, 2016)

b. Closed-cage aquaculture systems, i.e., fish farm egg by "Hauge Aqua", Neptun (by Aquafarm Equipment) and Eco-Ark.(Chu et al., 2020; Leow et al., 2020).

2.1.2 Classification of Mooring systems

The mooring keeps the fish farms in position and requires some degree of freedom to reduce stress under the application of varying external forces.

The mooring systems of aquaculture structures include a) single-point mooring, i.e. catenary, taut leg, single point, and b) multi-point mooring (i.e., spread moorings) spread line configurations (Fredriksson and Beck-Stimpert, 2019).

a) Single-point mooring aquaculture cages

Single-point mooring (SPM) aquaculture cage systems can rotate on their anchor points (Fredriksson et al., 2007b) based on tidal currents. Some examples of single point mooring are:

- surface floating gravity type cage (Huang and Pan, 2010)
- Submersible Ocean Cage Aquaculture Technology (DeCew et al., 2010b)
- Self-submersible SPM cage (Shainee et al., 2014).
- Submerged AQUAPOD cage (Clemence et al., 2011)

b) Multi-point mooring (i.e., spread moorings - spread line configurations)

Multi-point mooring grid systems are either square or rectangle-shaped grids. This configuration allows aquaculture cages to be connected to several mooring lines. The mooring grid system is designed to reduce cage disturbances caused by waves and currents

Some examples are

- a square-shaped mooring grid for one aquaculture cage that contains eight moorings and is the most popular grid one (Fredriksson et al.; Hou et al., 2017; Huang et al., 2007)
- a grid for two aquaculture cages in tandem that can have cages in a side-by-side arrangement (Huang et al., 2008;)
- a square-shaped mooring grid for four aquaculture cages or rectangle-shaped grid for four aquaculture cages in tandem where the cages could be in a side-by-side arrangement. (Fredriksson et al., 2004; Xu et al., 2012; Zhao et al., 2015b)
- rectangle-shaped grid for eight and sixteen aquaculture cages. (Zhao et al., 2015b; Bi et al., 2017b
- rectangle-shaped grid for twenty aquaculture cages. (Fredriksson et al., 2007b)

2.1.3 Classification of different types of netting

Net design is key to reducing the number of escaped fish, protecting against predator attacks, and helping to preserve optimum environmental conditions.

A structure must function in all environmental conditions, and it must be resistant to biological effects (e. g. biofouling).

Net components consist of net twines, woven nets, ropes, and pipes. Materials used include fibers, polymers, metals, and alloys. Natural materials (e.g. plant fiber) can be used because they are inexpensive and easy to obtain. However, plant fiber is likely to decompose when exposed to water for a long time. Using polymer material offers increased longevity, high breaking strength, and lightweight. Even with these advantages, polymer materials are still susceptible to the effects of biofouling. Biofouling causes severe problems and results in increased labor and maintenance. To circumnavigate this issue, researchers substituted the polymer material with metals and alloys because they are resistant to corrosion and biofouling. Accordingly, metals and alloys have been extensively used to make aquaculture nets (Chu et al., 2020; Dong et al., 2020; Tsukrov et al., 2011; Zhao et al., 2019). Most net materials used in field measurements and experimental tests are polyamide (PA) rather than polyethene terephthalate (PET) or polyethylene (PE) (Cardia and Lovatelli, 2015; Dowling, 2012, McKeen, 2016).

Nets can be knotted, or knotless based on manufacturing processes as both types are commonly used in aquaculture. The aperture shape significantly affects the flow field around the meshes (Bi et al., 2017). The different aquaculture nets used for fish farming are categorized as (Gansel et al., 2014; Tsukrov et al., 2011):

- nylon knotless square-mesh net (Raschel net),
- nylon knotted diamond-mesh net,
- nylon knotless hexagon-mesh net,
- PET hexagon-mesh net,
- steel diamond-mesh net,
- copper diamond-mesh net,
- flattened expanded copper-nickel diamond-mesh net
- chain-link woven brass diamond-mesh net and
- woven silicon-bronze square-mesh net.

2.1.4 Emerging technologies for aquaculture

Emerging technologies have the potential to enhance global seafood production and profitability. To improve off-shore aquaculture sustainability and profitability, novel and disruptive technologies, including genome editing, artificial intelligence, and the internet of things are considered.

Some of these technologies include:

1. genomic selection (GS) (Yue & Wang, 2017; Zenger et al., 2019; Houston et al., 2020),
2. genome editing (GE) (Gratacap et al., 2019),
3. Information/digital technologies include robotics, drones, sensors, artificial intelligence (AI), 3D printing, augmented reality (AR), visual reality (VR). These technologies are connected with farms through satellites, the internet of things (IoT) and information is provided through mobile phones and tablets. Some examples are briefly described below.

Robotics to carry out laborious work, including injecting vaccines (Lee et al., 2013), removing sick fish (Antonucci & Costa, 2020; Sun et al., 2020), inspecting and cleaning of the status of nets in the salmon industry. These leds to fewer human operations (Paspalakis et al., 2020) to survey the fish's health, monitor and prevent escapes of farmed fish biofouling prevention and inspection in fish farm (Ohrem et al., 2020) and fish behaviors (Kruusmaa et al., 2020). Drones are used for data collection above and below the water for the aquaculture industry. In combination with artificial intelligence (AI) and cloud computing, drones will cut costs and improve operations for the aquaculture industry (Chen et al., 2020). Drones can monitor fish farms on land and in sea, especially offshore aquaculture sites, including the checking of holes and damages in cages, which can be carried out by drones (Sousa et al., 2019). Sensors measure water parameters and monitor feeding and health status to reduce the wastage of feeds (Xing et al., 2019; Zhou et al., 2019; Antonucci & Costa, 2020; Su et al., 2020; Svendsen et al., 2020). 3D printing technologies to produce tools for aquaculture (Tiersch et al., 2020), printing hydroponic systems (Takeuchi, 2019), and fish robots (Clark et al., 2012;). The internet of things (IoT) is relatively new in aquaculture (Jothiswaran et al., 2020). The technology can provide big data (i.e. massive amount of streaming data) across the entire aquaculture industry)providing opportunities to gain and share information to be used for the optimization of operations (Kamaruidzaman & Rahmat, 2020).

Next, technologies provided by specific companies are reviewed.

2.2 INNOVASEA

Innovasea, a USA based company, provides end-to-end solutions for fish farming and aquatic species research. Although they are also active in fish tracking, land-based aquaculture, Innovasea specializes in open sea aquaculture, where they also apply intelligence systems. With 250 employees and 25 years of experience, Innovasea offers consultancy services, cages, monitoring and other tools and services.

In the following sections, we provide an overview of their relative cages, services, and costs. We also offer a summary of the meetings with Mr. Langley Gace, Senior Vice President (SVP), for strategy and business development.

Information obtained from http://www.innovasea.com/

2.2.1 SeaStation

The SeaStation is a proven technology. It has been implemented in several areas, including the Mediterranean and specifically in Paphos, Portugal, and Spain. The longest-standing installation is now in its 25th year. The SeaStation is a robust submersible system that can withstand high-energy ocean environments. The SeaStation ensures environmental conditions for the fish to also improve feed conversion ratio (FCR). An air compressor allows the SeaStation to be raised to the surface to allow:

Harvesting – Through a proprietary harvesting system.

Sampling – Fish samples to check growth and condition.

Desiccation – Cleaning once per week using wind and sun.

Maintenance – Simple and lower cost of maintenance.

SeaStation fish pens are also a development of InnovaSea Systems – their design allows for farm operators to "reduce the total cost of grow-out on medium-to-high energy aquaculture sites," according to the company. This technology has been used by InnovaSea customer Open Blue.

2.2.2 Evolution Pen

The Evolution Pen is a duck-and-cover system suitable for rough conditions. Although the cages are at sea-level during rough conditions, the system can be submerged to protect its structure and contents. Under normal conditions, the Evolution Pen is operated as a standard surface pen to facilitate use. Additionally, it has the following characteristics:

Modular design – Sizes ranging from 4,000m^3 to 20,000m^3 using interchangeable parts with the benefit of minimal engineering overhead.

Bottom moored – Connected to the grid at the bottom of the pen to reduce wear and makes it easier for boats to access the pen without having to navigate surface lines.

Water-borne feeding system – Distributes feed evenly across the pen from multiple points.

Copper alloy mesh netting – The copper mesh is an optional feature for long-lasting, predator-resistant, recyclable, and low-maintenance installation. It stays naturally clean, saving diver time and reducing insurance costs.

Nursery Net – This option simplifies the addition of smaller or younger fish without requiring a finer mesh for the overall pen.

Key safety enhancements – Full height, removable handrails, and non-slip fiberglass decking dramatically reduce slip-and-fall accidents.

2.2.3 Aquapod

The spherical cages are suited for open ocean conditions maintaining a diversity of species. The advantages of these submersible cages are:

Avoiding oxygen-depleting algal blooms that can be deadly to fish.

Finding optimal currents to keep fish active and healthy.

Locating ideal water temperatures to optimize growth and avoid thermal stress.

Avoiding parasites that concentrate near the surface.

Tensioned nets deliver consistent oxygen levels to the fish. However, this system is not sold anymore as it was found that the skeletal structure cannot scale as it will require supporting columns and can host parasites.

2.2.4 Cloud-Based Software, data acquisition, and analytics

Innovasea has developed a cloud-based aquaculture monitoring software that provides instant insight into all aspects of the farm's operation on a laptop, tablet, or smartphone. It combines real-time data with powerful analytics and reporting tools. The software allows data-driven decisions. The features include Cloud data management, Real-time updates, iOS/Android applications, user-configurable notifications, CSV downloads, and customizable reports. The software also allows plankton monitoring, biomass estimation, and feed optimization.

The length and weight of fish are estimated, and their growth is predicted using an AI camera shown below. The predictions provided can be used for budgeting.

Feeding optimization is supported by IP Cameras and Machine Learning. The method eliminating lost feed days and improves feed conversion ratios (FCR). Specifically, multi-Factor Feeding considers:

- Environmental conditions – Dissolved oxygen, water temperature, and currents play a key role in proper feeding. By monitoring these and other parameters in real-time, you can quickly determine ideal feeding times.
- Satiation – The satiation monitoring capability combines machine learning with species-specific data to track fish feeding behavior and alert operators when fish are approaching satiation. The solution improves scalability as it allows the monitoring of dozens of pens at the same time.
- Pellet detection – An IP camera captures video and provides live streaming to provide visibility into subsea feeding. This provides an insight into whether pellets are being ignored by the fish and sinking to the bottom of the pen. This adds another layer of important information in decision-making and reduces feed waste.

Additionally, InnovaSea offers automation and sensing solutions based on the needs and requirements of the customer. These include automatic feed dispersion, water quality sensors, cameras, and hydrophones. Information from sensors at the site is transmitted to the base, usually through systems like LoRa, but this will depend on system setup and distance from shore.

2.2.5 Information from stakeholder engagement

Key points:

The technology has been tested in the field (TRL9) offering ready to use, products together with the related preliminary study.

The technology has been implemented internationally in Hawai, North America, England, Norway, Bahamas and Korea. The company is currently considering the implementation of units in Greece, Croatia, Saudi Arabia, the UAE and Oman. In Korea the system is used for tuna fattening. Seabass and meager are also used in farms set up by Innovasea.

Offshore systems are vulnerable to extreme events, such as hurricanes and storms. Consistent currents gradually wear out an aquaculture system because of the daily tension created. The InnovaSea systems have been used and tested in areas with daily 20m/s currents, long waves (50m), and hurricanes.

The systems are scalable. An aquaculture farm can set up four (2x2) pens and then add pairs of pens to increase production.

The SeaStation is a compartmentalized pen with an integrated nursery net, large grow-out area, and mortality trap. The integrated nursery net releases fish into the grow-out area without fish loss. Dead fish are guided to the mortality trap by gravity and are enclosed to avoid contamination.

Although the systems can be setup in greater depth, 50-80m depth is in general the optimal depth for the setup of the aquaculture.

The system is equipped with feeding automation through water delivery. Water delivery results in less feed loss.

InnovaSea systems are set up 3-20 nautical miles from the shore, which, by experience, is a financially sustainable range.

The systems include automatic feed dispersion, water quality sensors, cameras and hydrophones, which allow for a minimum of one visit per week. However, in most cases the sites are visited daily for feeding, maintenance, and surveillance.

CAPEX: The technology cost is 50-100USD/m^3.

There is a 5-year depreciation timeframe for copper nets and 10-year depreciation timeframe for the cages.

Considerations for new open sea aquaculture stations:
Location and market requirements are the two main limitations and proper spatial planning is needed. It is advised that a doppler sensor is setup at the site to collect high quality current data to allow for the efficient design of the aquaculture system. In addition, it is advised that a complete economic model that includes the foreseen expenses of the aquaculture is taken into account as well as the availability of interested buyers for sea-products.

There was no loss of system or stock reported for InnovaSea cage technologies.

InnovaSea supports interested parties at the research, design and implementation stages. Among others they offer a full suite of desk studies such as GIS consulting and economic plan.

Countries such as Saudi Arabia, UAE, Oman and the US are interested in moving aquaculture further offshore. For example, the US is investing 45m USD in offshore aquaculture. Covid-19 pandemic has affected market behavior. In the Azores where fish was sold as fish and chips since products were not uptaken by the HORECA sector.

2.2.6 Typical costs

Innovaea provided rough pricing for a 16 pen (2x8 cells) in both 150 m and the suggested 80 m. The pricing included is a feed distribution system with cameras as well as the pump and silo system. The costs do not include a vessel that is assumed to be sourced locally.

Grid System

2x8 grid (16 pens)

i. 80m depth-assumes flat bottom

If grid system was filled with SeaStations, Price $820k

If grid system was filled with Submariner Pens, Price $720k

ii. 150m depth-assumes flat bottom

If grid system was filled with SeaStations, Price $1.056M

If grid system was filled with Submariner Pens, Price $960k

Pens

Submariner 14,000m^3 Kikko (large mesh 3.7), Price $425k/pen

SeaStation 14,500m3 Kikko Kikko (large mesh 3.7), Price $720k/pen

Feed Distribution and Cameras (per 2x8 grid)

1. Feed Distribution (all the piping, conduit and connections required to deliver feed), Price $578k

2. Cameras (multiple cameras in each pen to properly observe feeding. Total of 16 pens), Price $406.8k

IP Camera system in conjunction with Modular Feeder includes equipment for remote feeding

3. Modular Feeder (does not include the vessel)

Total Price for 2 pumps and 8 silos $1 million

Pricing does not include installation or modifications to the feed vessel

4. Nursery Nets (typically, one needs one nursery net for every three grow-out pens)

Price $30k

Harvest Seine Net (typically one needs one a harvest and net for every eight pens) Price $23.2k

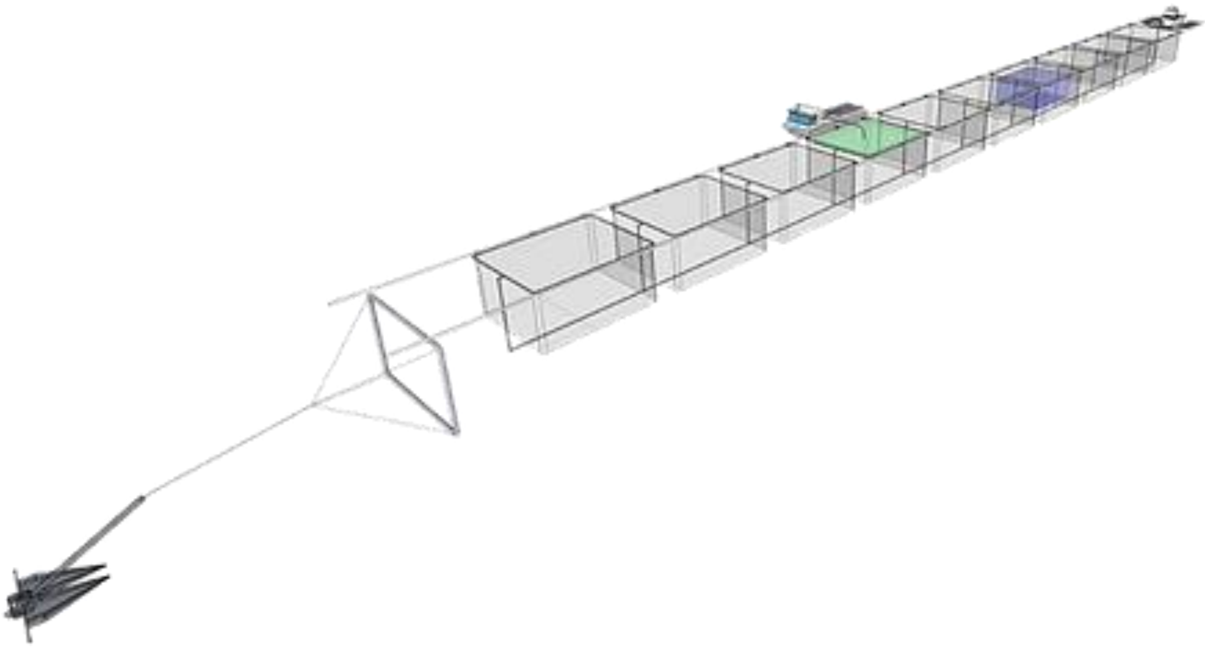
2.3 GiliOcean Technology

Information obtained from https://www.giliocean.com/

2.3.1 SUBflex

The company offers a submersible flexible cage that has a single mooring. The single mooring allows 360-degree rotation aligning the cage with the current to reduce resistance. The design has the benefit of withstanding harsh weather conditions. Additionally, the flexible design allows constant movement that facilitates the mobility of organic matter within a 1000-meter radius, minimizing the impact to the seabed and water column. The life span of the cage is projected to 20 years which reduces the overall cost. Another benefit is scalability due to a modular design. Cages can be placed in series, and all are supported by the single mooring.

In case of harsh weather conditions, the net cage system can submerge within 9 minutes. An automated remote submersion mechanism exists. However, as mentioned in the meeting, there has always been human presence while submerging the structure in anticipation of extreme weather. In the case of submersion, water-borne feeding is applied.



2.3.2 GoSmart

The company utilizes precision farming techniques that include data acquisition through specialized hardware and analysis. The analysis provides information on water quality and fish biomass, mortality, and behavior. The goal is the increased utilization of resources and increase in yield.

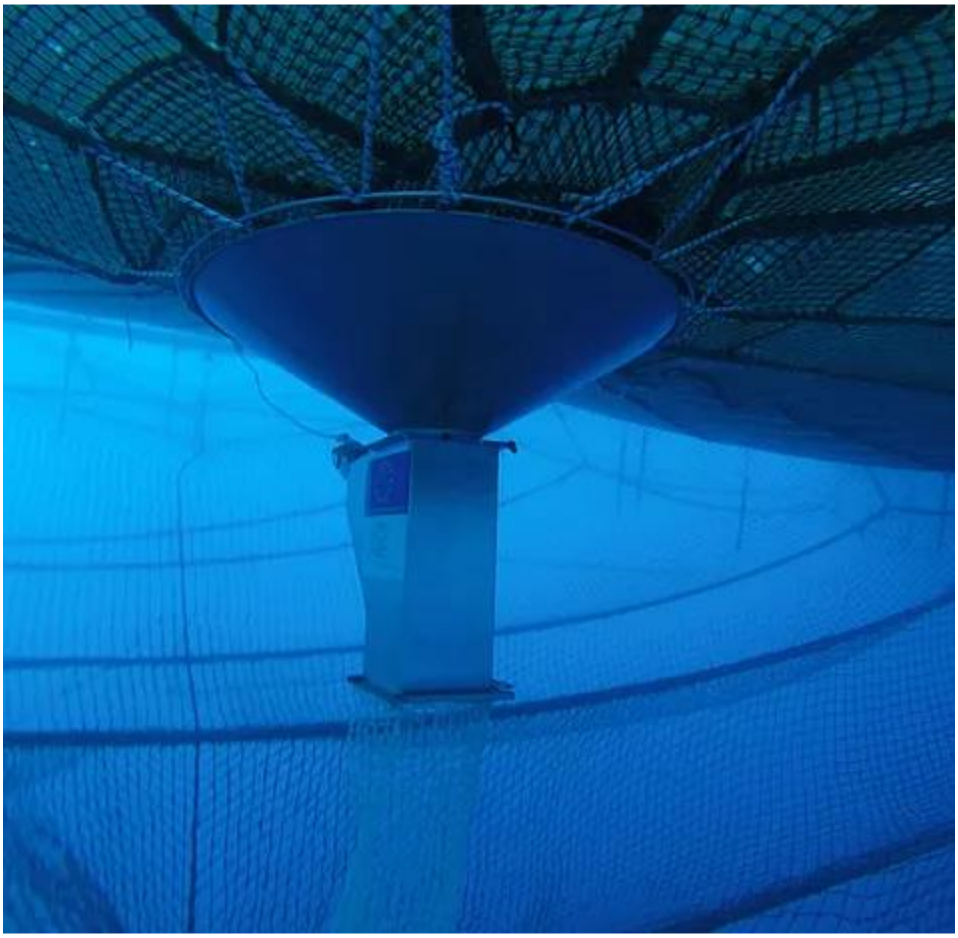
For data acquisition, the GO Smart BioCam is used. The GO Smart is a Biomass estimation camera that also provides data analysis capabilities such as fish weight and distribution of cage population. It has integrated oxygen and temperature sensors and allows feeding calculation. During feeding the system connects directly to the feeding boat to allow real-time monitoring of the feeding task. Additionally, the system is power autonomous through solar power. It is accompanied by a web application and the company provides cloud data services and management software. One GO Smart BioCam unit is allocated per cage. The depth rating is 60m. The accuracy of fish weight reported is 2% which allows the calculation of feed to reduce overfeeding. The monitoring of the cage allows the reduction of pollution and waste.

2.3.3 GoSmart Software Integration

The web application allows user friendly display of information together with the ability to produce reports. The interface connects to the biomass and feeding camera, mortality counter, and dissolved oxygen and water temperature sensors.

2.3.4 GoSmart Mortality Counter

The mortality counter provides counting, but also separates the dead fish from the cage. The mortality numbers are provided remotely to the farmer. The dead fish are collected via a stainless-steel box preventing the spread of diseases due to parasites, bacteria, and viruses. The system provides updates every hour.



2.3.5 Information from Stakeholder Engagement

The company has also designed specialized vessels and inland facilities that are fit for purpose. A specialized boat of cost 2M dollars was designed in Israel and produced in Turkey. The boat represents a large part of the CAPEX. The boat is designed to reduce operational cost, a logistics base accommodation, Crane, Multipurpose deck, integrated feed tangs, and an automatic feeding machine.

Since 2018, GiliOcean has, for interrupted periods, produced fish and distributed to local market. The system is operational in existing farms in the coast of Israel. Target markets are USA, Colombia, Central America, Israel, Vietnam, India.

The system is submerged at a wave height of 2-3m and higher. The system has withstood 11.5m wave height without any damage to the structure or the fish. The maximum wave height it can withstand is 17m (designed based on simulations and storm modeling at the site).

Installation characteristics and size:

Placed 15Km from the shore.

Current scale in South Israel: unit at 75-82m depth capacity of 1600Tn

Max volume per cage that has been implemented till today is10K m^3. The next model will be double that amount.

For the single mooring system, the diameter of the circle that the system rotates around the anchor is about 1600 m. A 2 km^2 wide area needed due to the rotation of the cages.

Currently, a unit operates at 75-82m depth, 15km off the coast

The specifications below affect the spatial planning process:

40 m from the top of the cage to the seabed since:

a) 24 m cubical cages, planning to have 30 m cubical cages

b) 6-10m above the seabed when submerged

c) Since there is a maximum of 17m wave height, the system needs to be submerged at least 40m depth (sea-surface to top of the cage)

Scalability:

The current cages hold 10000 m^3 with plans to create a new product of 20000 m^3. The cages can be made square or circular. The sites can be scaled (2,4,6,8 cages and so on). The maximum potential capacity with a single array is 6000T annually.

Submersibility and security:

Feeding occurs while the system is at the surface. The system is submerged only during storms. The longest it was submerged was 12 days. Although the fish were not fed, their metabolism and growth performance were better after the period of fasting. The submersion can also be remotely controlled, but it is preferred to submerge the system in-situ, which takes 15 minutes. There are visits every day and guards at night to guard it against theft. The vessel can also remain at sea overnight.

Anchoring:

Single mooring means that the system can rotate 360^{o,} allowing the dispersal of nutrients and less environmental impact. The company is also testing the use of a second mooring. The units have been tested at 300 Tn for a 6-cage installation that occupies a radius of 800m. Therefore, single mooring requires a large sea area. With two moorings, the area decreases, and so a second installation can be placed to produce more fish. In Israel, the wave currents are mostly moving in two opposite directions (south to north and north to south). Therefore, they are considering a double mooring oriented to face the currents on the narrow side.

Financials:

There is a need to use the economy of scales with 1200 – 1300 Tn production to break even. The company seeks projects over 4000 Tn, which are considered to be profitable. The design and implementation of the facility take 18 months. Furthermore, 24 months are needed from placing fishlings to harvest. The nets are specialized (EcoNets) and have a lifespan of 20 years. The growth rate is reported to be 18% higher than traditional farms.

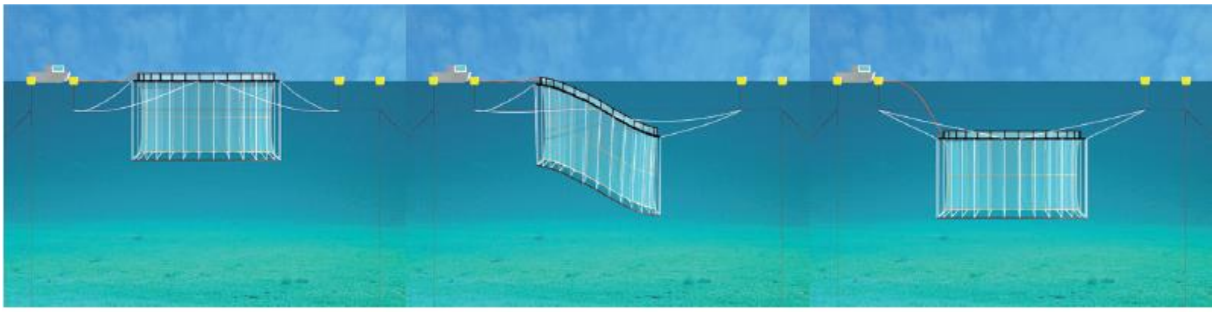
2.4 Badinotti

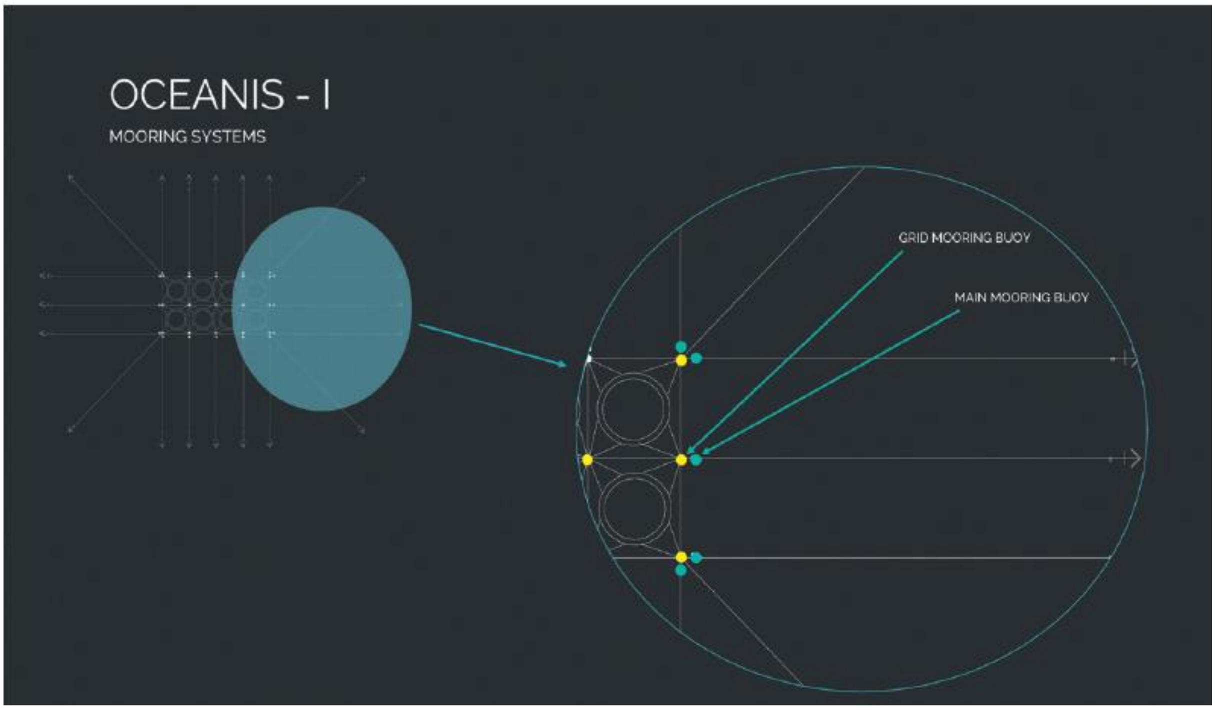
http://www.badinotti.com/empresas/

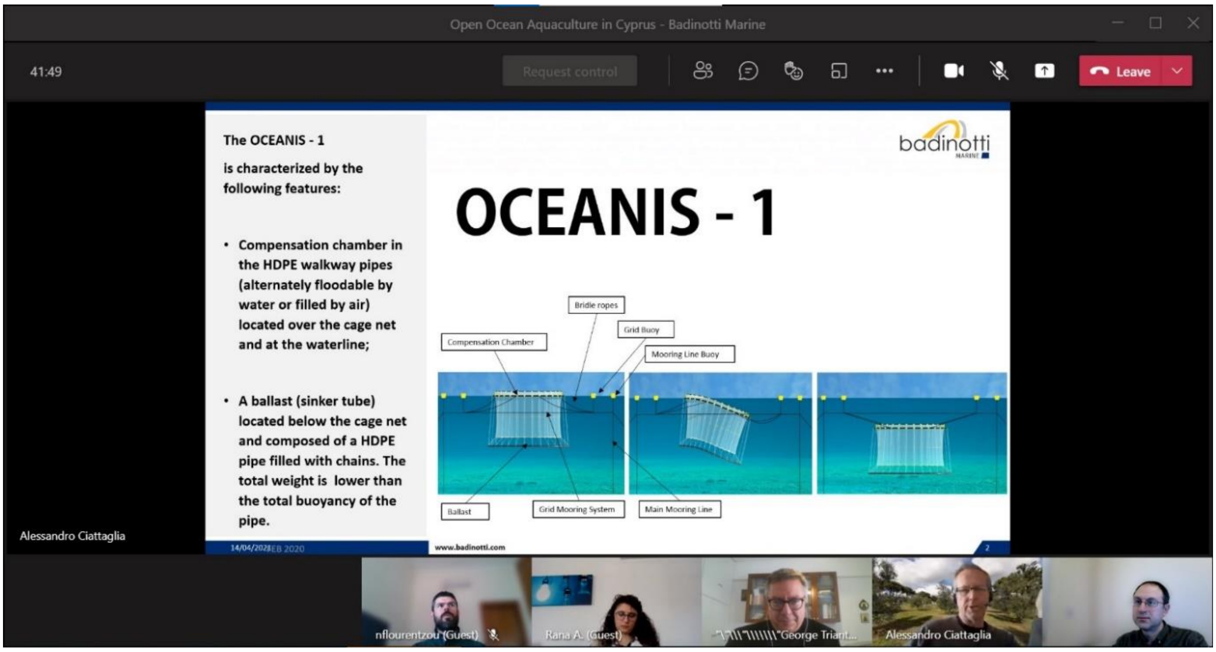
badinotti.com/wp-content/uploads/2018/03/CAGE-FARMING-EQUIPMENT_PRESS.pdf

The Oceanis cages are submersible, and according to Badinotti, are preferable due to avoidance of ice flows that may cause damage, avoidance of surface toxic algal blooms, reduction of sea lice, improvement in oxygen levels, safety from large wave heights, and avoidance of high visibility making them vulnerable to criminal activity.

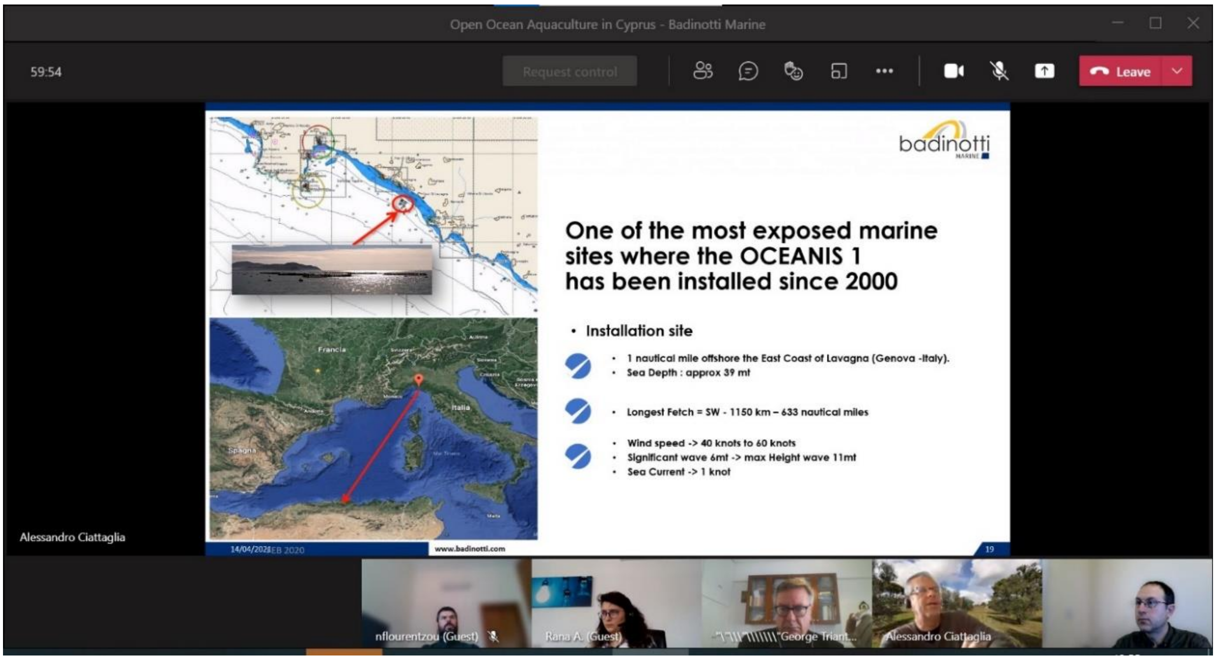
2.4.1 Oceanis I

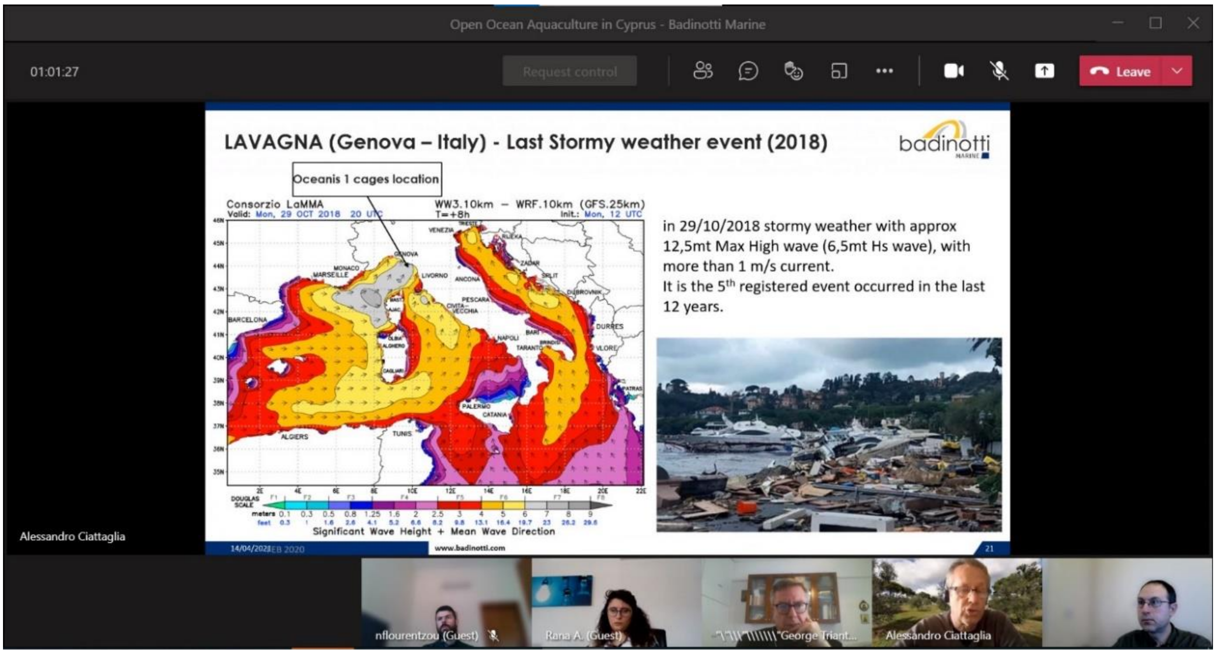




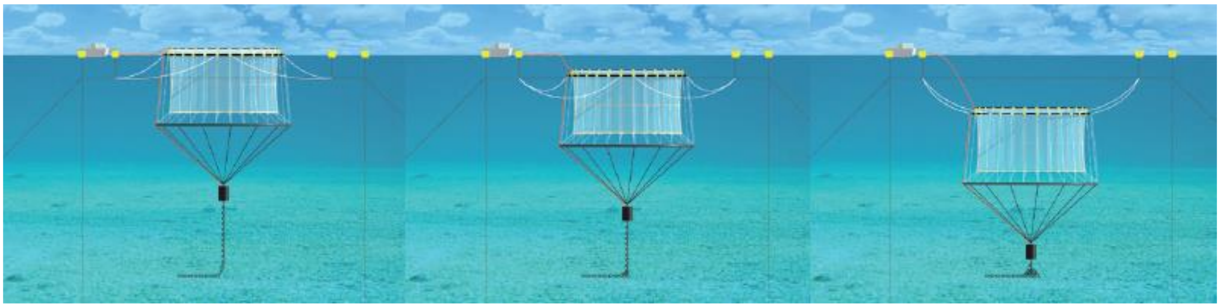


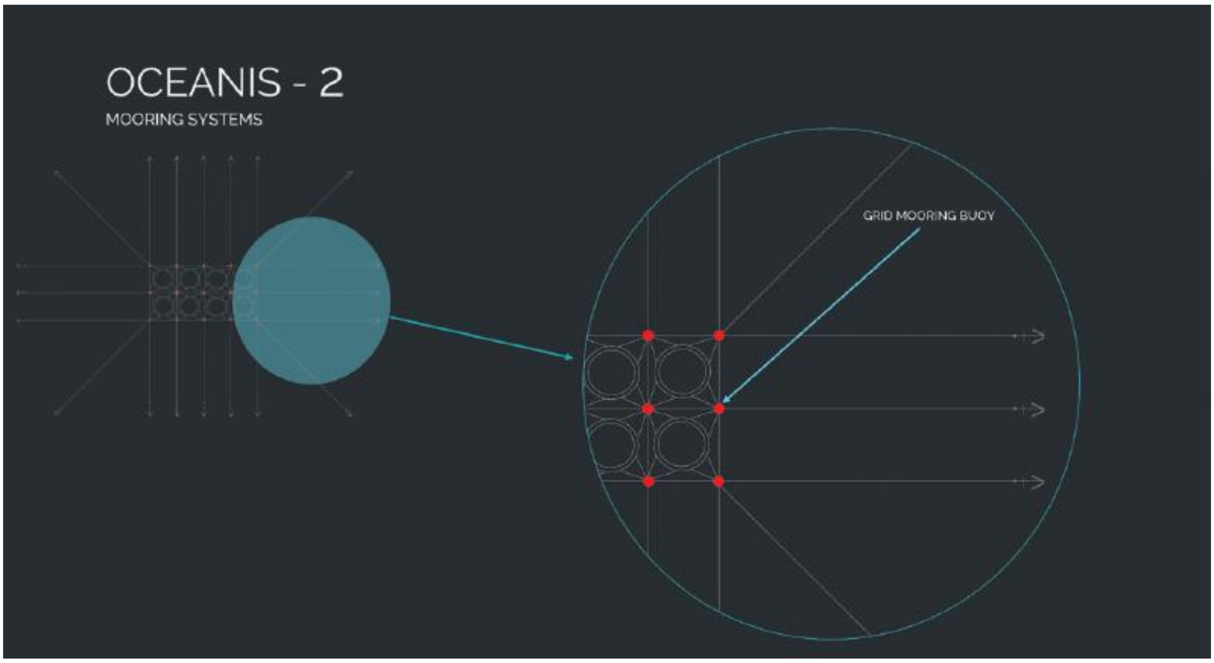
Oceanis I is associated with low maintenance and investment cost. It is a conventional approach with a circular design that provides easy access. There is a possibility for the cage to be submerged when needed, for example, in cases of high waves. Moreover, it can be submerged most of the time at depths between 15 and 20 m. The cage can be floated in five minutes. However, 20 minutes is recommended for the fish to acclimate to the change. Oceanis I has been in operation for more than 20 years. Data from the most exposed marine sites were provided in the stakeholder engagement session with Bandinotti. The net and materials used are standard, similar to those used in conventional aquaculture. There is zero visual impact on the system. This is important for aesthetics, avoiding theft, and allowing other maritime activities.

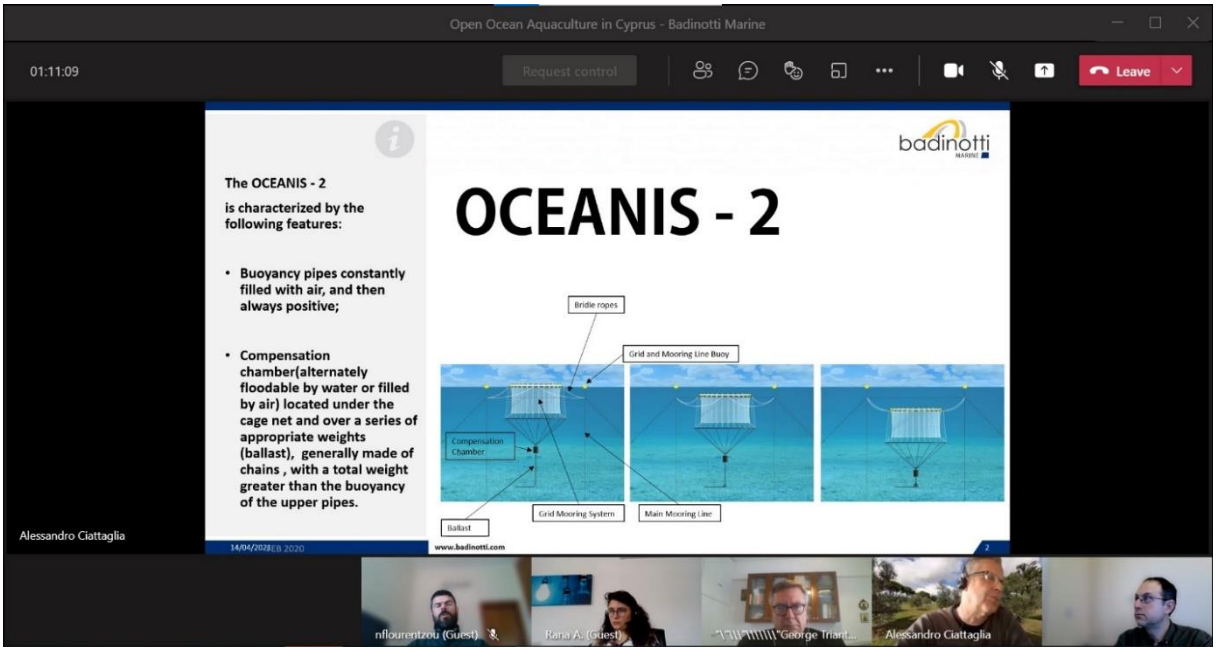




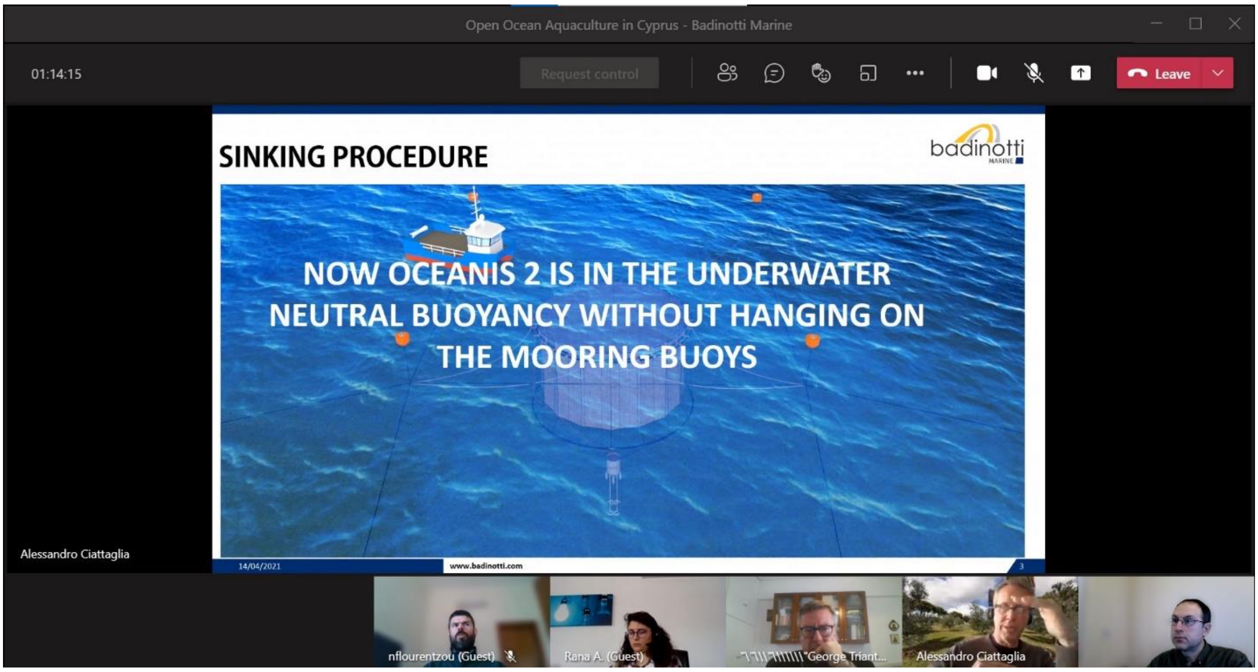
2.4.2 Oceanis II

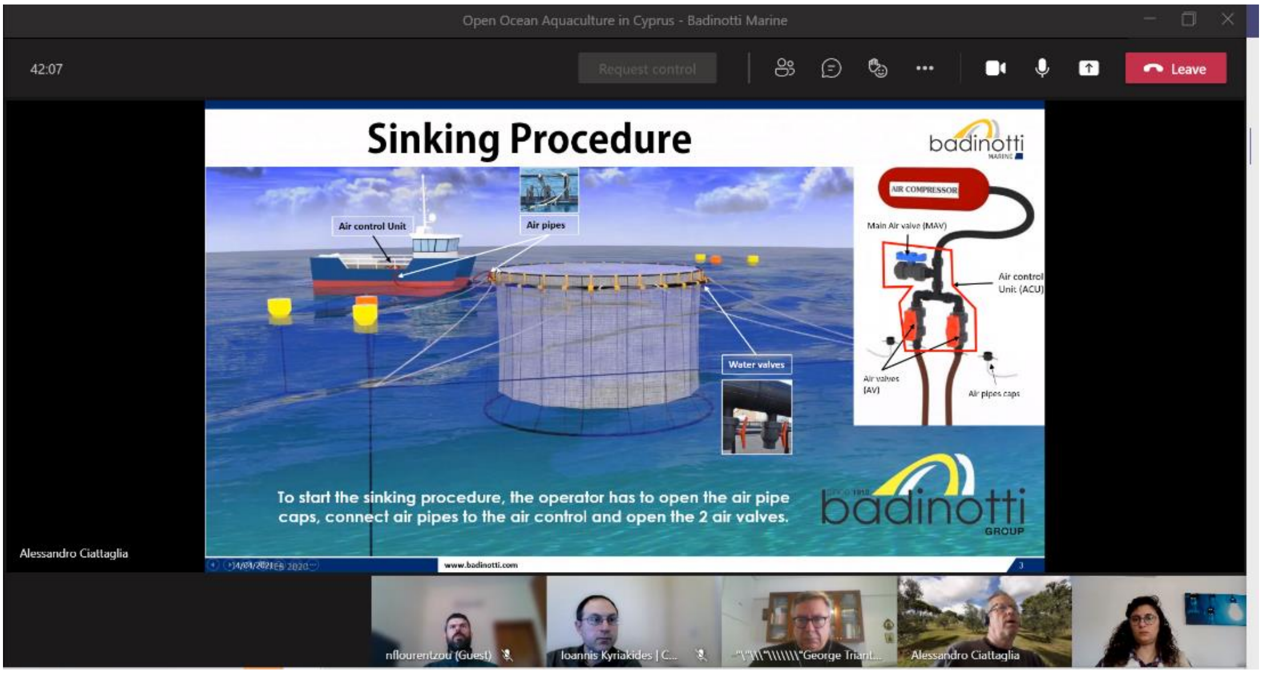


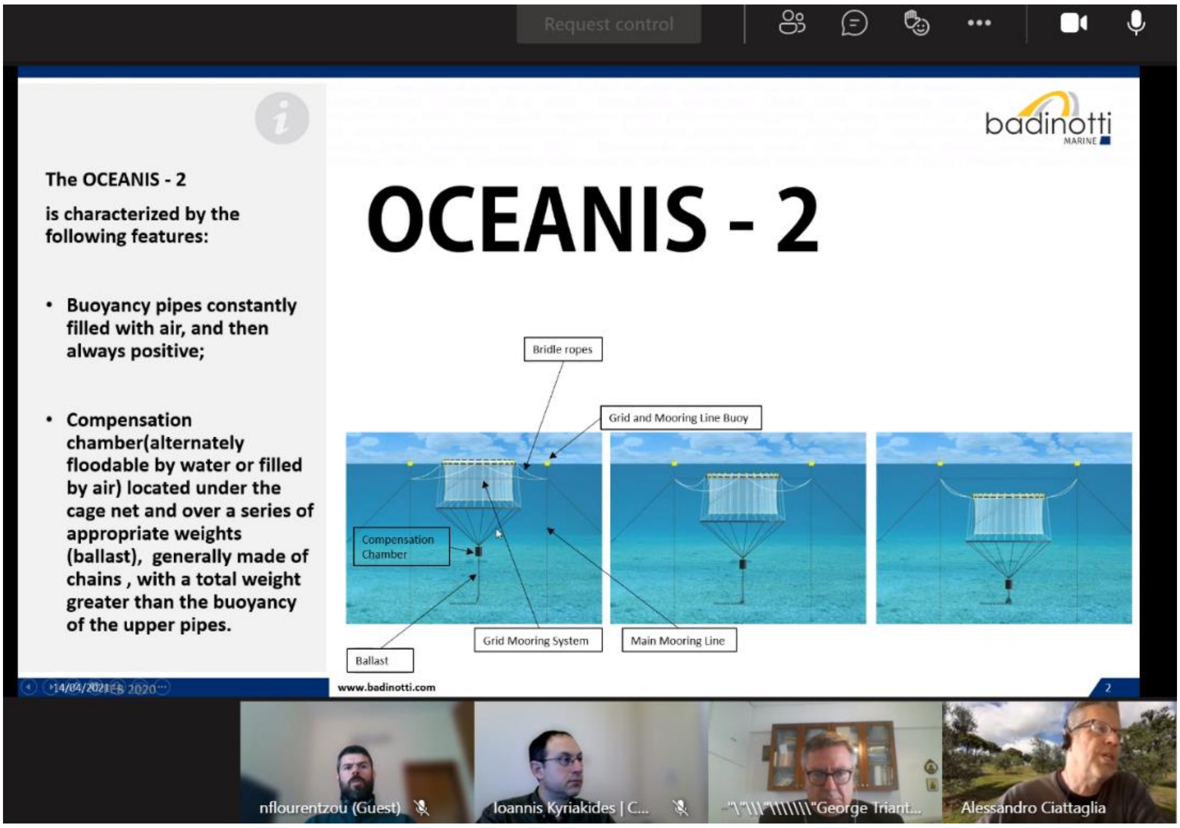


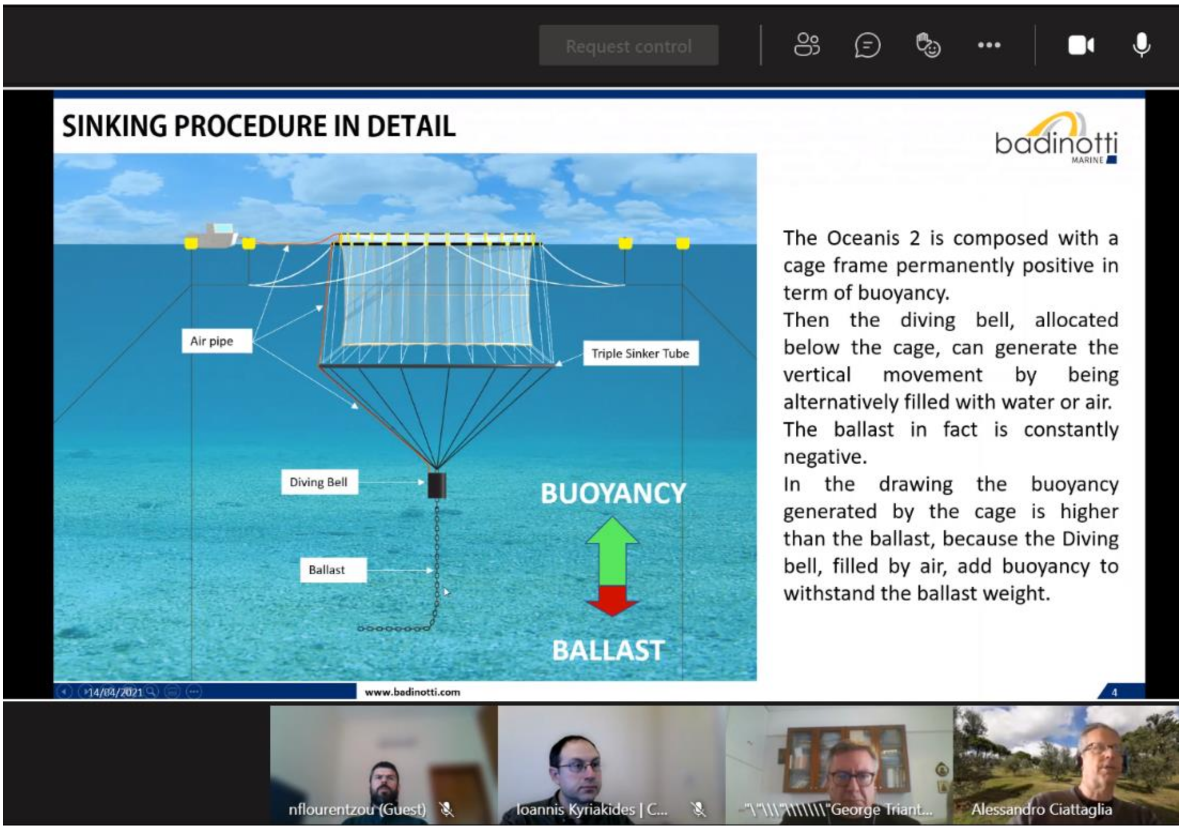


Oceanis II also has a conventional circular design. Similar to Oceanis I, it can be submerged on-demand or permanently at 15 to 20 m. The Oceanis II has the additional characteristic of maintaining its shape during the sinking and resurfacing. This reduces the stress and improves the well-being and welfare of fish. The mooring system is also conventional; however, it requires slightly deeper locations compared to Oceanis I, which range to 50-60 meters. The system needs to be custom-made for the location and depth it needs to sink to. It takes 25-30 minutes to lift up the Oceanis II, with faster sinking, which is not recommended considering the welfare of fish.






Request control
badinotti
MARINE
The OCEANIS - 2
is characterized by the following features:
• Buoyancy pipes constantly filled with air, and then always positive;
• Compensation chamber(alternately floodable by water or filled by air) located under the cage net and over a series of appropriate weights (ballast), generally made of chains , with a total weight greater than the buoyancy of the upper pipes.
OCEANIS - 2
Bridle ropes
Grid and Mooring Line Buoy
Compensation Chamber
Grid Mooring System
Main Mooring Line
Ballast
www.badinotti.com
nflourentzou (Guest)
Ioannis Kyriakides | C...
Alessandro Ciattaglia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SINKING PROCEDURE IN DETAIL
badinotti
MARINE
Air pipe
Triple Sinker Tube
Diving Bell
Ballast
BUOYANCY
BALLAST
The Oceanis 2 is composed with a cage frame permanently positive in term of buoyancy.
Then the diving bell, allocated below the cage, can generate the vertical movement by being alternatively filled with water or air.
The ballast in fact is constantly negative.
In the drawing the buoyancy generated by the cage is higher than the ballast, because the Diving bell, filled by air, add buoyancy to withstand the ballast weight.
www.badinotti.com
nflourentzou (Guest)
Ioannis Kyriakides | C...
Alessandro Ciattaglia

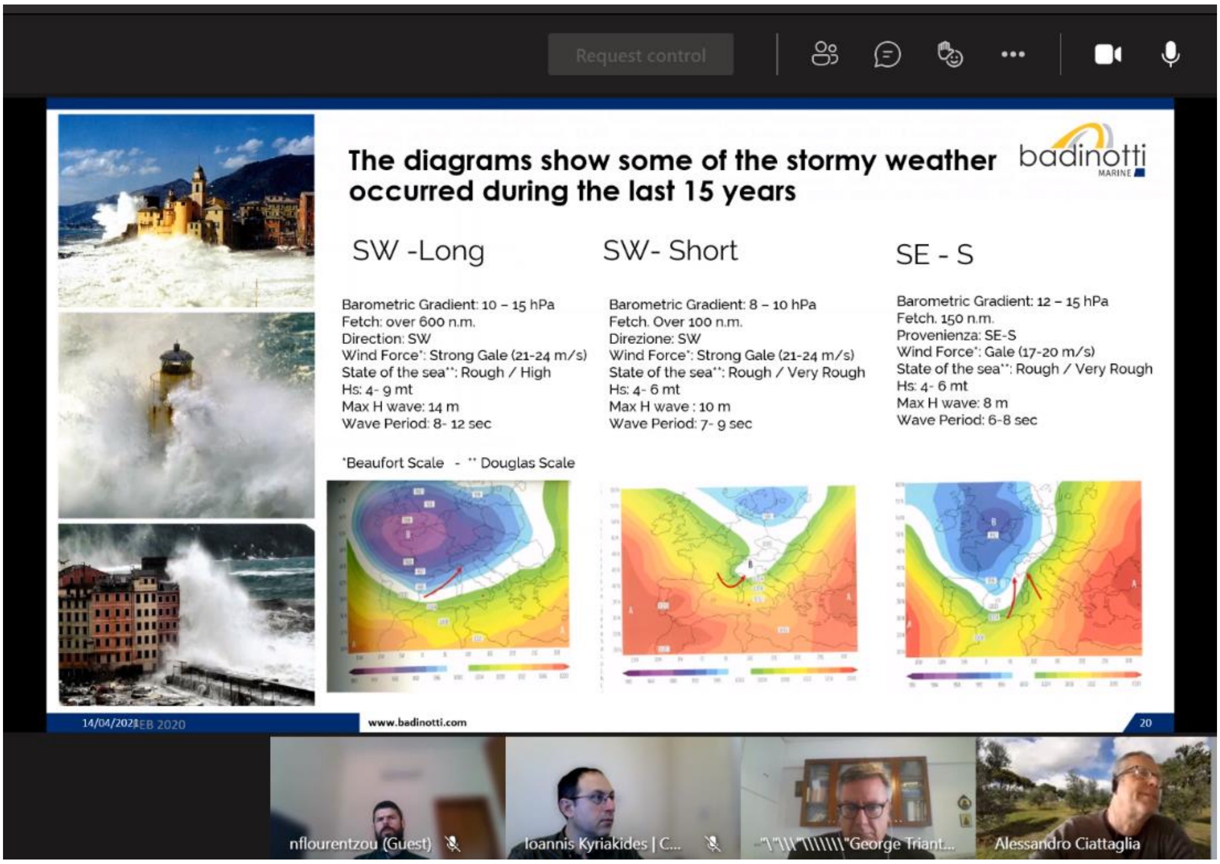
2.4.3 Information from stakeholder engagement

Locations: The technology has been implemented in Chile, Peru, Western Canada (Vancouver), Mexico, Finland, Algeria. Cages are now operational in Italy, Tunisia, Martinica.

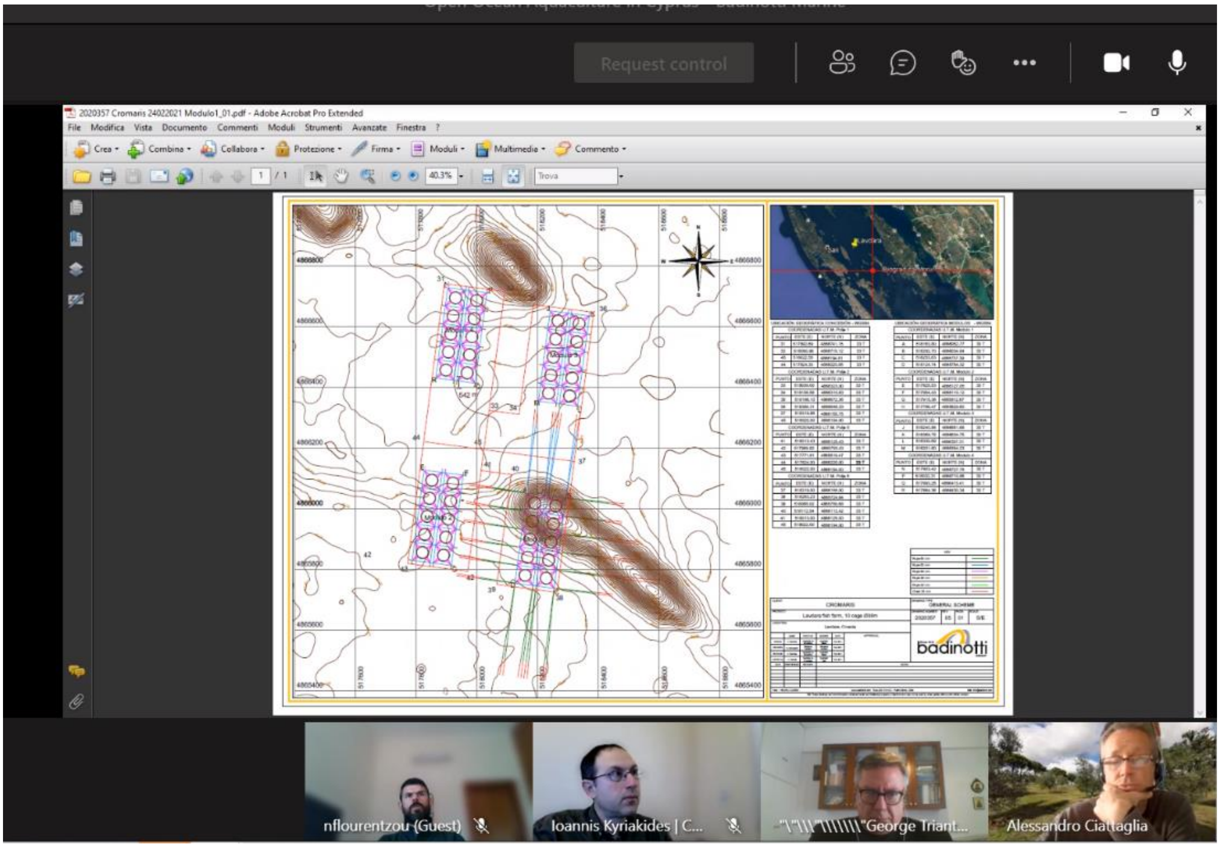
Cultivated species: Sea bass, sea bream, and salmon

Environment and resilience: The cages can withstand strong weather of 3.5 m significant wave height (approximately 7 m) and 1m/sec current. As they were submerged, only one cage was lost during an extreme storm event (where Andromeda lost many cages in Spain) because of the drag of the mooring.

The mooring is built based on data from the area. Relying on historical data is often not enough because of climate change and extreme weather events. It is recommended to use extreme value analysis for the 50 and 100-year return periods to engineer systems suitable for a specific area. Due to the tropicalization of the Mediterranean area, it is not reliable to use historical data. Therefore, the most important information to have is current data. The Norwegian standard suggests using spot current data for three months that is multiplied by 1.2-1.4 to correct for the development of stronger currents in the area.



Seasonality is not taken into consideration. Orography is taken into consideration as currents are expected to be increased above underwater mounts.



Cage size in relation to the climate

Low energy: 25 m diameter (although smaller cages can be used, the costs are not significantly reduced. Therefore, a cage with a diameter shorter than 25 m is generally less profitable)

Medium energy: 30-40 m diameter

High energy: Submersible cage recommended.

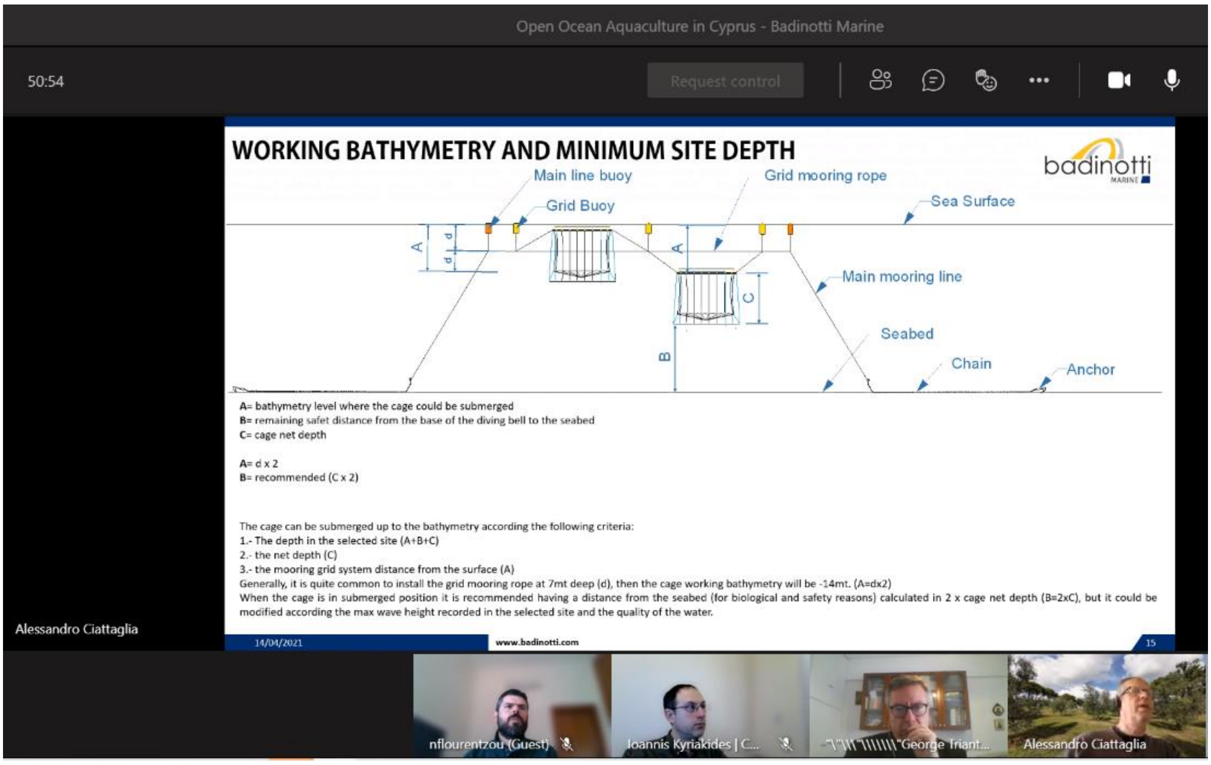
Scalability

Cages can be installed as a grid system. A farm can scale up by adding new cages as conventional cages. Anchoring needs to be placed at 12 degrees at least.

Visual impact: With the submersion of cages, only buoys are visible.

Theft is the main problem for the floating cages. Submerged cages are safer from environmental conditions or illegal activity. However, they need a feeding system with the technology currently not well developed.

Depth of installation and anchoring



If submersible, the depth between the top level of the structure and the surface is about 10-15 m. The optimal depth is calculated based on the height of the cage and the distance from the mooring. In Italy, Oceanis I is installed at 40m, in Algeria at 35-45 m, and in Mexico 60-90 m. The area needed for the mooring system is approximately 4.2 times the depth. If the depth is 100 m, the length of the chain is 420 m (from buoy to anchor). This can be reduced to a factor of 2.5 to 3.0 with concrete blocks.

Feeding

Oceanis is usually used at the waterline position. The cage remains submerged only during bad weather. A feeding system is not available when submerged. In Finland, this system is installed for trout production and remains submerged (under ice) for several months. No feed is provided to the fish. However, this is mainly an experiment to see if the fish can survive under continuous submersible conditions. In Russia, some systems deliver feed to submerged cages as a common practice.

Automatizations

No remotely controlled technologies for mortality rates or water quality are available by the company, so external providers are recommended.

Financial considerations

Some insights received that consider the financial aspect is that the maximum profitable distance is 1 hour from the nearest port. However, other factors affect this aspect, such as the speed of the boat and the fuel consumption. Feeding occurs 1 or 2 times a day. Depreciation for the cage is 8-10 years. With good maintenance, the cages can be operatable for over 20 years. Mooring needs to be serviced every 2-5 years (but inspection on an annual basis). Nets need to be serviced every year and changed 2-5 years, depending on the species and nets used.

2.5 NSK Ship Design

NSK Ship design is a Norwegian designer with a focus on fish farms and fishing and cargo vessels. Many designs exist on the website https://www.nskshipdesign.com/ship-design/. In this survey, the scope is concentrated on fish farms.

2.5.1 NSK F3 300 FjordMAX

This is a semi-closed fish-farming concept unit for fjords and benign waters. It includes a mechanism for drying and transporting waste to the shore. The unit increases circulation via high volume oxygen-rich seawater injection by delivering seawater from 60m depth. It also produces its own oxygen. The length is 155m, and the production is 3x100.000 m^3. It has a DNVGL class.

2.5.2 NSK H2 Havfarm Dynamic

This is a self-propelled unit. It includes integrated fish feed silos and water injection for adjusting the oxygen level. The design can sustain high water heights with protective skirts that reduce current effects on the fish. The unit is constantly moving within a large operational area, eliminating the effect of waste on the environment. The heading is also changed to improve fish welfare and oxygen level based on the weather conditions. The unit was designed to operate independently of service vessels by using Rail Mounted Service Units and a semi-automatic integrated live fish transfer system. Therefore, the risk of cross-contamination due to the visit of ships is minimized.

The length is 304.2 m, and the production volume is 4x100.000 m^3. It can hold 1180 m^3 of feed, 2600 m^3 of fuel, and 100 m^3 of freshwater.

2.5.3 NSK H1 Havfarm Stationary

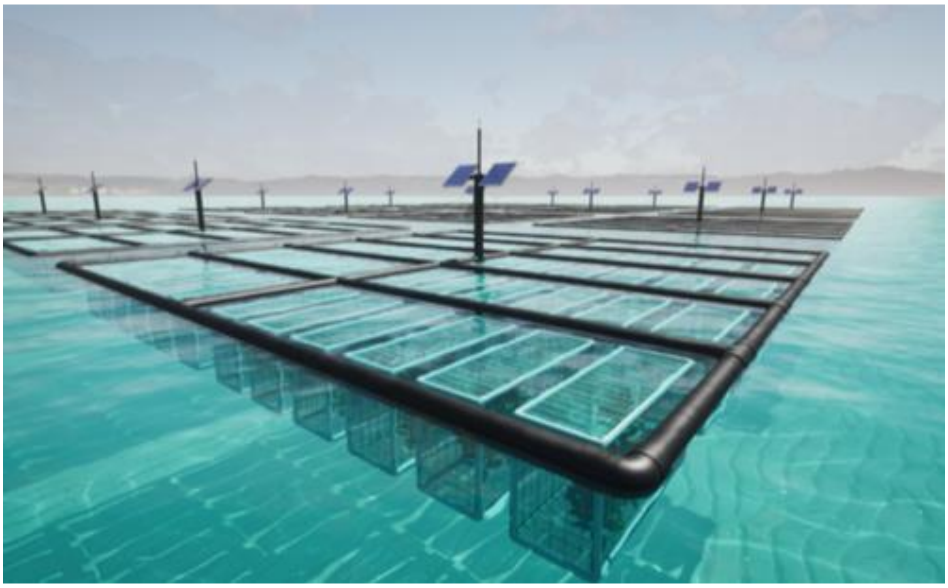
This is a moored unit that rotates based on the sea currents (weather vaning moored turret). It has integrated fish feed silos and a water injection system to optimize oxygen levels inside net pens. The protective skirts reduce current effects for fish. With the added overpressure from the water injection system, sea lice are kept outside the unit.

The weather vaning system allows the increase of the area of spread of waste-reducing the effect to the environment. Moreover, the weather vaning system reduces the weather-induced load on the unit.

The unit works independently of service vessels via Rail Mounted Service Units and semi-automatic integrated live fish transfer, therefore, minimizing cross-contamination with service ships.

The length is 385 m, with a production volume of 480.000 m^3. It holds 1800 m^3 of feed, 145 m^3 of fuel oil, and 90 m^3 of fresh water.

2.6 KZO Sea Farms



This is a submersible structure, the Submersible Seaplant Structure, that was made of High-Density Polyethylene pipes. Designed for sea-plant crop yields, this design is also considered when designing new types of aquaculture stations. Some of the benefits that this structure provides are the following:

- Protection from hurricanes as the pipes can be filled with seawater for the submersion of the structure;
- Production of higher yields due to the above submersible feature that allows the structure to be positioned appropriately for optimal cultivation;

Improvement in quality control with a resilient, transparent, and secure distribution supply chain will be mandatory for meeting sustainability certification standards.

2.7 SalMar

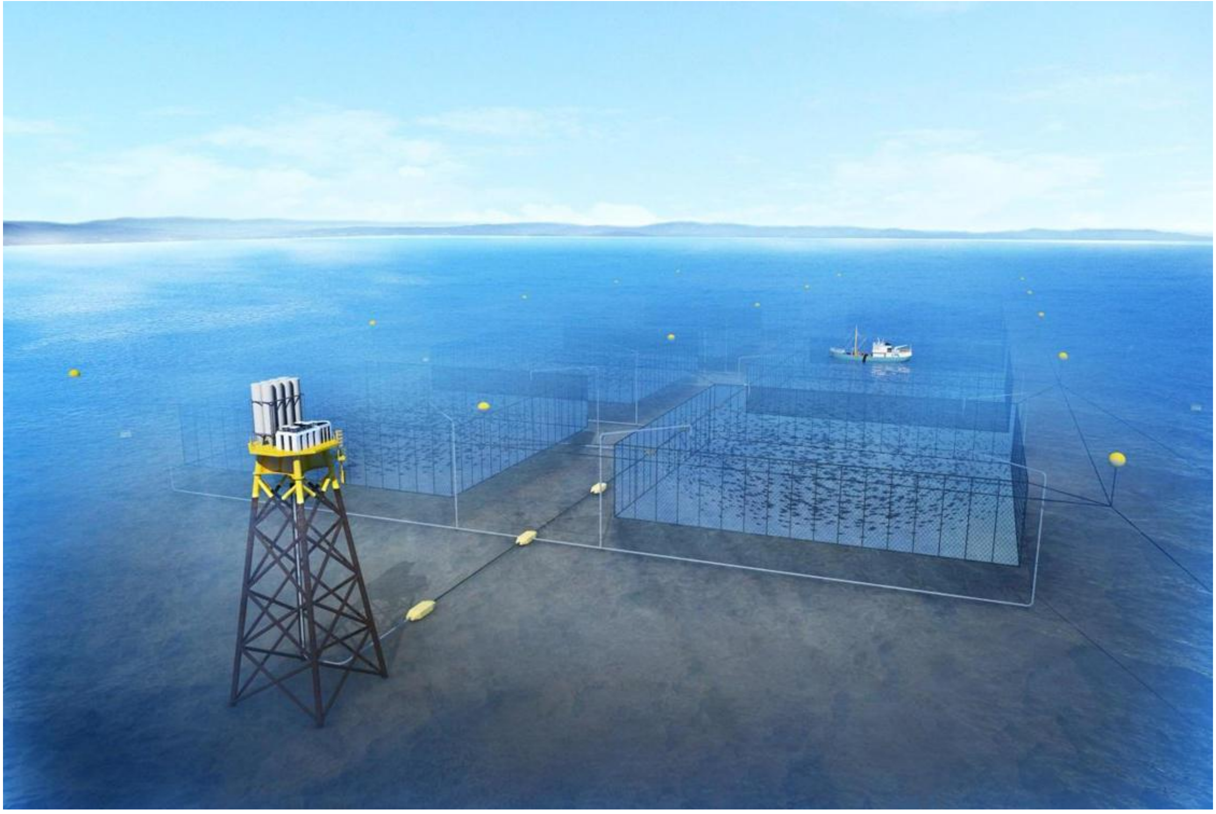
https://www.salmar.no/en/offshore-fish-farming-a-new-era/

Ocean Farm 1 is an offshore fish farm representing a full-scale pilot facility of 6.000-tonne capacity. It is designed to test both biological and technological aspects of offshore fish farming. It has a height of 69 m, a diameter of 110 m, and a volume of 250.000 m^3. Partners in the Ocean Farm project include industry - Kongsberg Maritime, classification authority - DNV, and research institute - Sintef. As of August 2021, two production cycles at Ocean Farm 1 have been completed, producing a total of 10.000 metric tons of salmon. SalMar is not only considering sites for salmon production in Norway; other possible areas include the east and west coasts of the United States, South America, Iceland, and New Zealand.

To further accelerate growth, a new structure, Ocean Farm 2, has been designed for fish farming in the open ocean. This new design can withstand a 100-year storm while the facility is foreseen to have a production capacity of 23.000 tonnes round weight and a production volume of 760.000 m^3.

2.8 NIPPON Steel Engineering

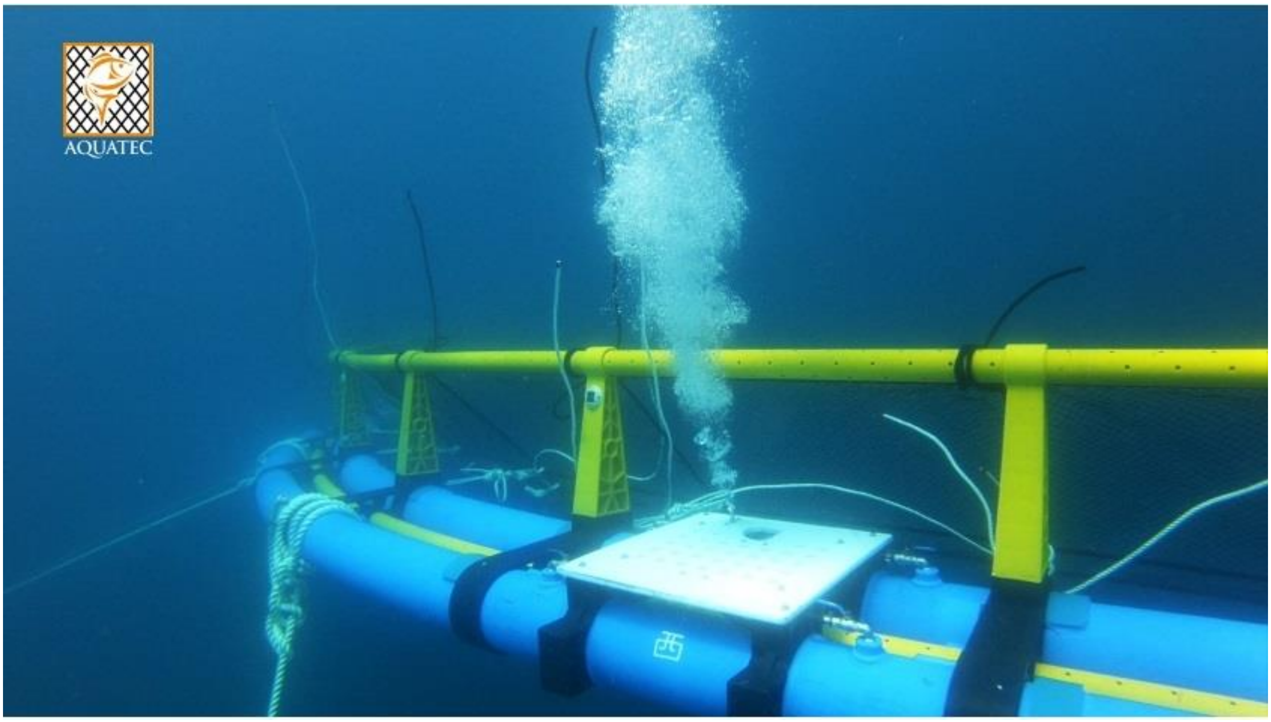
https://www.eng.nipponsteel.com/english/whatwedo/businesscreation/aquaculture_system/large_scale_open_water_aquaculture_system/



This is a fish cage system for large-scale open ocean farming. The design allows a significant increase in fish cage size to benefit from the economy of scales. Numerous simulations were conducted to assess the effects of waves and currents by using computational techniques and scale models. The results showed that the performance of this fish cage system is adequate for offshore waters. Moreover, an automatic feeding system has been devised for the feeding process that uses an underwater pipeline, through which fish feed can be directly supplied to the cages, while a platform has been employed for feed storing purposes. A 300-square meter platform was used for experimental purposes in Sakaiminato City, Japan, at 15-meter depth, and a new demonstration site is foreseen at 60 m depth.

2.9 AQUATEC

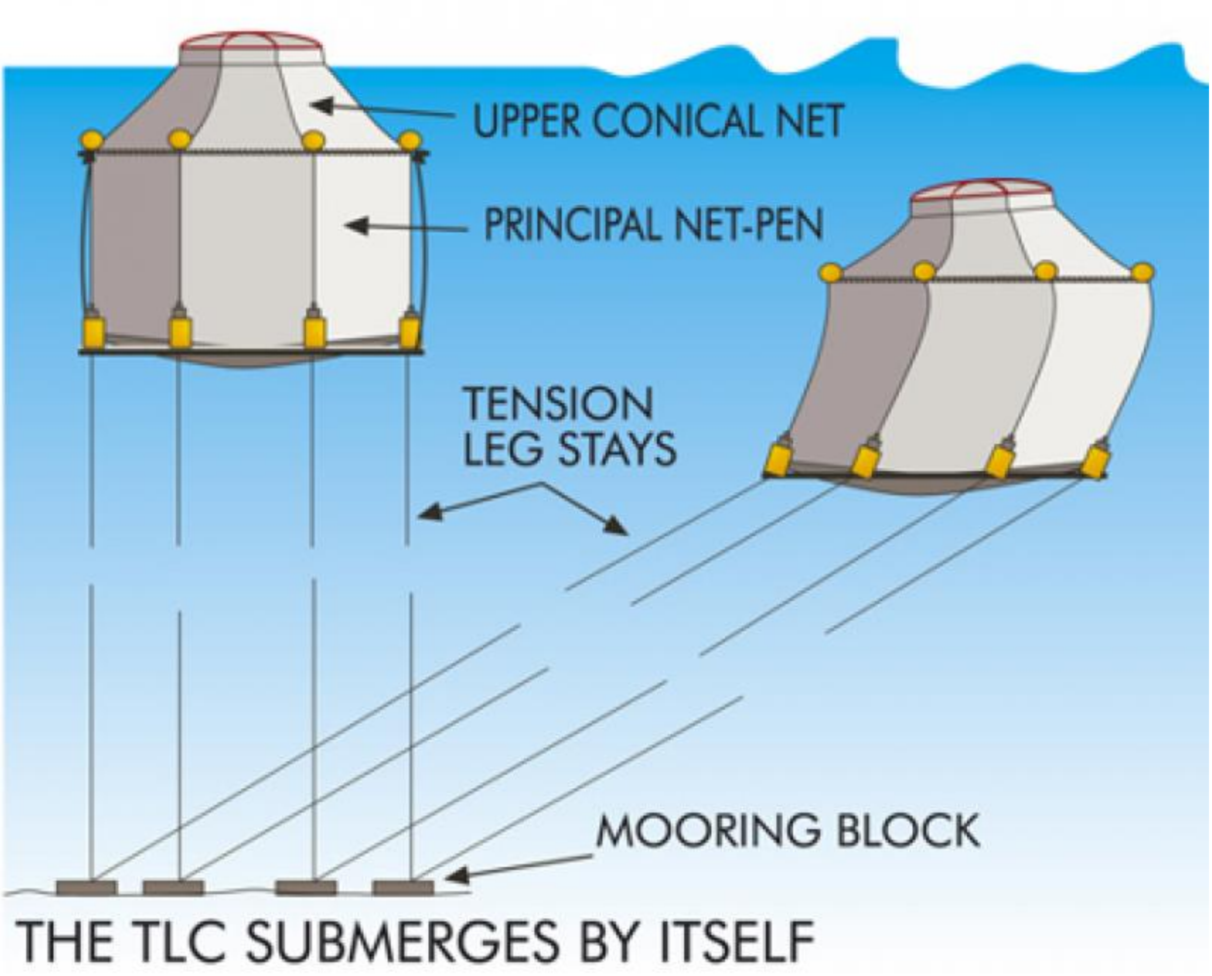
https://aquatecindonesia.com/product/offshore-submersible-cage/



This is an offshore submersible cage that is designed to sustain the typhoon storms often occurring in Southeast Asia. It can also withstand wave heights up to 7m. The Aquatec Offshore Submersible Cage can be submerged in 5 minutes, with parallel submerging of multiple cages. Two people are enough to complete the operation, and refloating takes 10 minutes. The frame can be floated to maintain the net and harvest the fish. It has applied over 15k units in Indonesia.

2.10 REFAMED

https://refamed.com/gabbie_mare/tlc_system.html



This Tension Leg Cage design allows the dispersion of wave energy. The design allows motion similar to seaweed to minimize strain on all cage components. Additionally, this design retains its volume to improve fish welfare while each cage is not connected to adjacent ones allowing independence in the movements. The Tension Leg Cage adapts to the wave conditions, can be submerged in rough sea states, and is available in a variety of sizes up to 15.000 m^3. In locations where tidal ranges are between 2 m and 10 m, tension-leg cages are either completely submerged at high tide or have loose netting near the top at low tide because of their fixed depth. This type of cage has been deployed in Italy, Spain, Portugal, and Brazil.

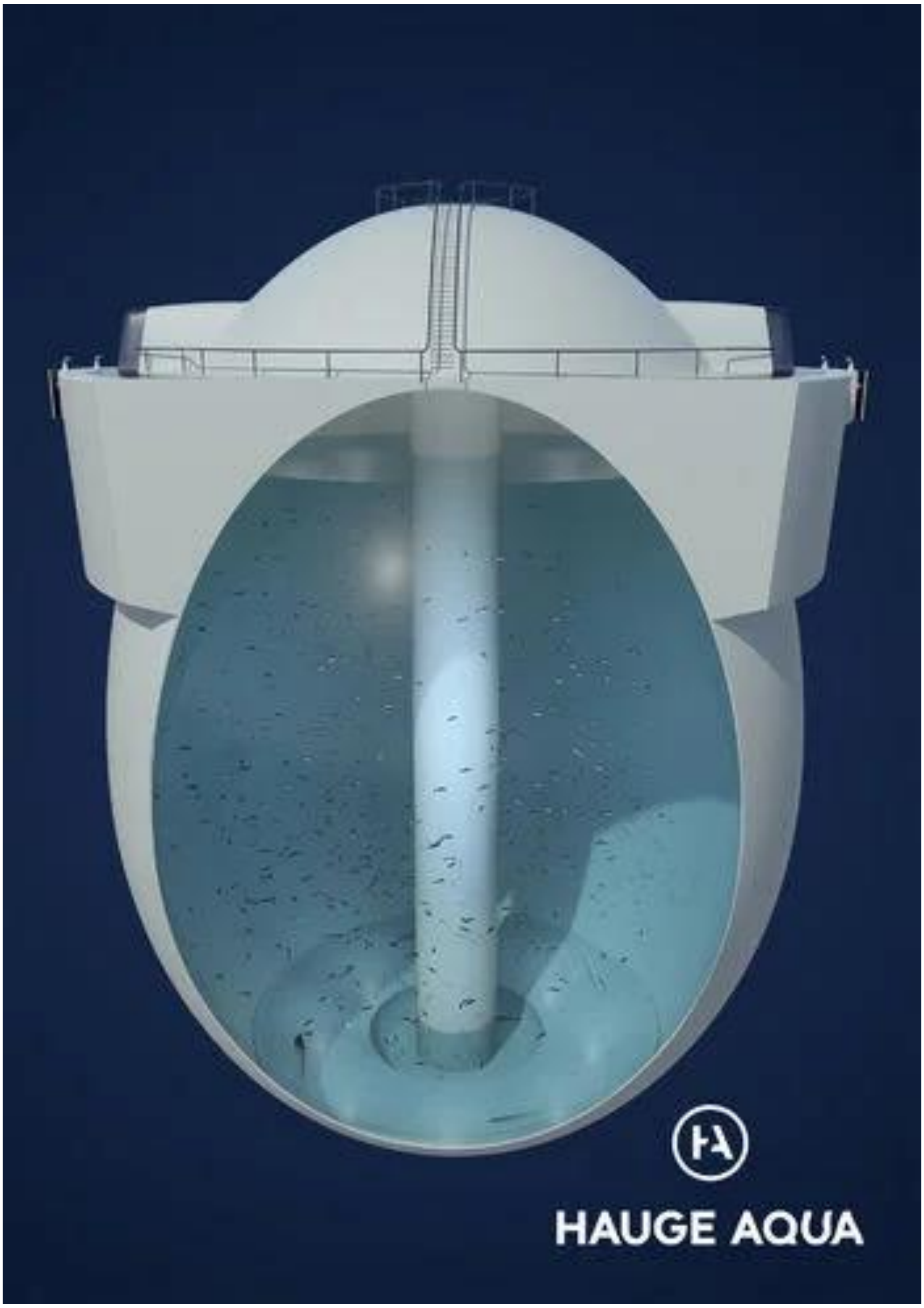
2.11 AQUAFARM

https://aquafarm.no/#!/concept

This closed cage design is reinforced with steel in areas of high stress. It is equipped with a pump system that extracts large volumes of water. The conical-shaped bottom allows the collection of waste. This closed design has the benefit of eliminating diseases and fish escape and provides low mortality due to the protection from predators.

2.12 Hauge Aqua

https://haugeaqua.com/



The Egget design creates a sheltered workspace to ensure the health and safety of staff. Construction material is a composite sandwich formed in a seamless double curved surface. There is water intake at the bottom, providing both a safe environment and water flow. The enclosed design allows for more accurate feeding with no waste and the water inlet and outlet located at the bottom of the structure are double-secured to eliminate fish escape. The design also keeps the fish safe from predators. Moreover, light and oxygen levels can be controlled at any time and also de-gassing of carbon dioxide.

2.13 Aquatraz

https://aquatraz.com/en/

The Aquatraz solution targets the elimination of sea lice and fish escape using deep lice skits and a rigid steel structure. The structure can be lifted above water for cleaning, disinfecting, and maintenance.

Water is taken from depths that are free from sea lice and algae and circulated within the cage. The working conditions of staff are improved as the structure has wide walkways and handrails. Improvements in the second-generation design are a new lifting system that does not rely on energy supply from a boat.

2.14 Shenlan

https://www.seafoodsource.com/news/aquaculture/china-shifting-aquaculture-production-to-higher-value-species

https://www.fishfarmingexpert.com/article/china-plans-salmon-farm-130-miles-from-shore/

This submersible design can dive in depths of 50 m, accommodate 50,000 m^3 of water, and adjust the depth to water temperature. This allows the farming of coldwater fish in the warmer waters of the Yellow sea, China. The stable design keeps away predators. Shenlan 2, the descendant of Shenlan 1, is considered the largest fully submersible structure for salmon farming globally. Its height is estimated to be 80 m, compared to the 35 m of Shenlan 1, and will accommodate one million fish, a significant increase from Shenlan 1 with 300,000 fish.

2.15 ACE FARM

http://www.ace-sg.com/acefarm/

https://www.sfa.gov.sg/food-for-thought/article/detail/closed-containment-systems-an-answer-to-rising-eco-threats-30-by-30-goal

The ACE FARM (or Eco-Ark) is a floating fish farm that uses offshore and marine technology, IoT, and includes an automated feeder system and tank cleaning system for a safe water discharge back to the sea. The effects of the spread of waste to the sea are mitigated by such technologies. The solar panels on the roof allow for the energy autonomy of the fish farm. Moreover, it has an upper deck for post-harvest work, allowing productive and sustainable fish farming practices like cleaning, processing, and vacuum packing for direct distribution. This platform has been deployed in Singapore.

2.16 OCEAN ARKS TECH

Autonomous ocean aquaculture. https://oatech.cl/

The benefits of this technology include:

- High production: Up to 3900 metric tons
- Movement to best locations for fish production, levels of oxygen, temperature, and other relevant variables, avoiding areas of acidity and algae bloom.
- No need for anchoring
- Avoids bad weather conditions
- Has long operational autonomy of 25 days, having facilities of up to 20 crew members
- The ship moves close to coast for harvesting and maintenance provided that the proper harbor facilities exist.

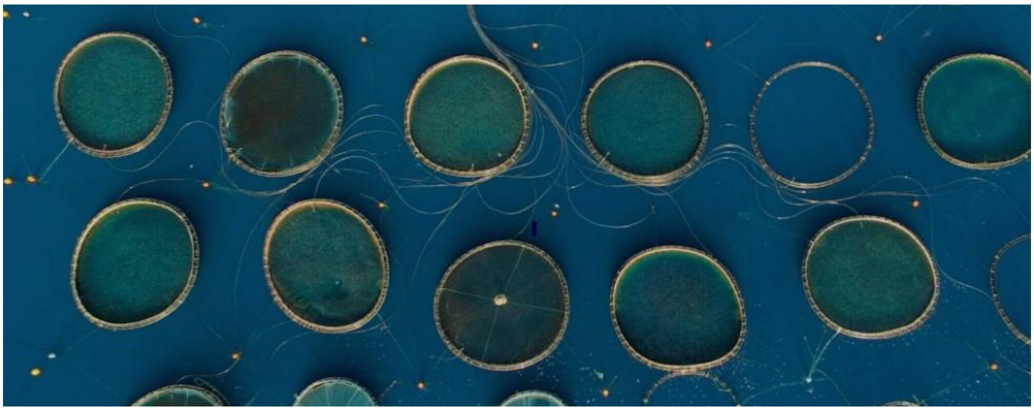
The benefits come with a high level of investment. The design inspires lower-cost designs that can be locally developed specifically for the Mediterranean region

2.17 Traditional cages

Coastal aquaculture, including local companies, use round pens with nets extending to the bottom. The cages are moored to the bottom while nets are kept in shape with weights. The number of cages can be increased to allow increases in production. If need be, the cages can also be towed. Feeding and fish retieval s facilitated by the open cage design.

Local companies have extensive experience in the installation and use of these cages. The team met with Kimagro ltd director, Antonis Kimonidis. The company was one of the first to be established on the island and Antonis has oceanography and technology background and experience.

Antonis stressed the ease of use of the cages as opposed to alternative options he has tried to use or has seen being use by other companies. He also said that at the moment they have aquaculture sites installed at 60m depth with some moorings reaching 80m depth, making the suggestion that the cages could be used for open sea aquaculture. Similar arrangements have been used in Madeira, Portugal and have been proven to withstand strong wave action, when coupled with suitable mooring.



Cages used traditionally in coastal aquaculture

2.18 Discussion on Existing Technologies

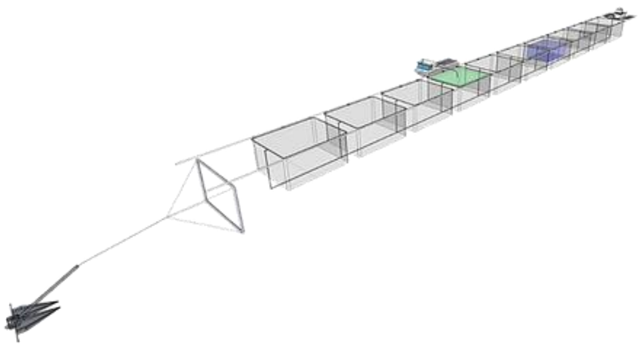
The aquaculture technologies surveyed represent a wide selection of different types of cages and mooring types, suitable for different magnitudes of production, depth, and budget. Bearing in mind that different approaches have been made with different considerations in mind and are suitable to different environments the goal of this section is not to make a direct comparison between technologies and select ones that are universally the best. Rather, this section identifies aquaculture technologies that are suitable to the Eastern Mediterranean region. Therefore, the identified technologies relate to a specific area and opinions, and their selection targets their use in business case scenarios that would be more appealing to investors and producers for Cyprus and Eastern Mediterranean aquaculture.

The rationale behind the preference for some of the technologies is the suitability to the Eastern Mediterranean region that is based on a) the size of the countries and budgets considered, b) the need to provide a solution that will be acceptable to current producers and investors that offers the possibility to expand existing operations and ensure acceptable levels of risk. The selection of technologies was done in consultation with stakeholders that included local aquacultural companies, technology providers, and marine engineers. The local aquaculture companies are possible early adopters of OS Aqua and the new proposed OS Aqua facility design. Therefore, their views significantly influenced decisions. To limit the number and complexity of business plans the consortium has considered only a small number of technologies, selected from the list of technologies provided in the previous section, as other factors such as the areas selected, type of fish farmed, availability of local expertise for maintenance, financial projections would increase the dimensionality of the design and make the analysis of the various options intractable. Therefore, this section provides reasonably sized input to other work packages and especially WP7 responsible for developing feasible business plans, avoiding an overwhelming number of options.

Even with the availability of modern monitoring systems and automatizations, it was found, through stakeholder engagement, that producers still require the human presence and frequent visits. This fact has prompted the consortium to select conventional designs suitable to open sea areas versus deep-sea areas that will improve the chances of acceptance by relevant stakeholders. Moreover, the consortium proposes a novel design that combines the benefits of larger investments scaled down to the economic reality of Cyprus and East Mediterranean countries. Therefore, from the technologies considered, the consortium has left large installations suitable for very large-scale production, associated with large CAPEX and OPEX, for future consideration. Similarly, larger depths and larger distances from harbor facilities that may pose a risk in financial feasibility are omitted. The focus remained in technologies that are suitable for the Mediterranean region and a new proposed design that will be considered subject to the availability of future funds.

Since the following assessment of the different types of aquacultures is based on the opinions of stakeholders that include local aquaculture producers and marine engineers, the analysis does not provide a conclusive decision on which types of aquacultures will be suggested for Cyprus and the Eastern Mediterranean by the consortium. The analysis, instead, serves to refine the selection of the many technologies identified to limit the options that need to be further considered for financial analysis for practical purposes. However, this refinement in the selection of technologies does not place a limit on the choice available to possible investors, as the methodology adopted and the information acquired in this project facilitates the development of new business cases based on any of the identified technologies.

The first type considered is a conventional type of aquaculture with many years of experience of use in harsh weather conditions. This type includes the types offered by Innovasea (SeaStation) and Badinnotti. The benefits of the technologies offered are the resilience in harsh weather conditions, offering the capability of submersing the facilities to avoid extreme events. Moreover, these conventional facilities are similar to the existing facilities used by producers with aquaculture facilities located closer to the shore. The maintenance and feeding methods are known to the producers and personnel with the required skills already exist. The risk is that these facilities have not been used in waters of depth 100m-200m. Therefore, the consortium will provide a recommendation in including this type of technology in the business case scenarios while consulting with experts on the feasibility of operating at larger depths.



The second type considered is the single moored, GiliOcean. This is a distinct design as it allows the spread of waste in a large radius by rotating 360 degrees, unlike the facilities mentioned above, which only move to the surface and below based on the weather conditions. The GiliOcean station can also be submerged and is, therefore, protected in case of bad weather. The other benefit is the scalability, where additional cages can be attached to the structure utilizing the same mooring. Compared to other designs such as Badinnotti and Innovasea, the fact that the GiliOcean design utilizes more space per cage due to its rotation, although beneficial to the environment, it requires more space to operate than what is available for a certain production level. The design has been significantly studied and tested and provides a good candidate for business plan development. However, local aquaculture producers and marine engineers have questioned the long-term endurance of the design due to its many moving parts that may deteriorate over time. As the stakeholder opinions are taken into serious consideration, this deliverable suggests that this design could be considered together with other, more readily acceptable technologies for the business plan or used to influence the concept of a new design.

Enclosed structures, including modified ships that farm fish inside the hull, have the benefit of eliminating escapes and protecting the fish from predators. The environment inside the enclosure can be fully controlled in terms of light and oxygen levels. Moreover, staff has the possibility to work in offices inside the solid structure that potentially offers safety and improved working conditions. One concern on modified ship enclosed structures is that the ship motion will have adverse effects on the welfare of the fish. In stationary structures, further study is required on the cost of installation and maintenance. Moreover, these structures will require skills or facilities for repair and maintenance that may not be present in Cyprus and other Eastern Mediterranean countries, thus reducing the pace of adoption.

Solid structures such as the ones offered by SalMar are suitable for harsh open sea environments. Specifically, Ocean Farm 1 is testing biological and technological aspects serving as a pilot facility and designed for salmon farming. This type of technology is promising. However, expected to represent a significant investment. Some design ideas from this technology and the following ship-shaped aquaculture technology are used to create a new design of an aquacultural facility that is suitable to Eastern Mediterranean country size and available skillset and shipyards.

Ship-shaped structures are suitable for open sea by design and have the ability to either relocate in bad weather or rotate based on environmental conditions. The benefit to the environment is significant as the ability to relocate also reduces the deposit of waste in fixed locations. However, this type of facility represents a significant investment that the consortium feels that will not be made based on the size of Cyprus and Eastern Mediterranean countries. However, if new markets open and are directly linked with Cyprus for exports, then such designs could be considered, however, at a smaller size. These designs, however, have generated the concept of a new catamaran-shaped aquacultural facility that is purposely designed in the appropriate dimensions that will allow its development and maintenance in Cyprus shipyards.

3 Design of a new open sea aquaculture station

In view of the fact that current conventional OS Aqua designers do not recommend depths of more than 80m, and also due to the large investment required for the ship-shaped technologies, a new design was envisioned. The new design combines all benefits from different types of aquacultural designs surveyed earlier. It does not, however, claim to be the best option universally. Instead, it is customized to the size of Cyprus, the waters of the Eastern Mediterranean, and the acceptability from local aquaculture producers and marine engineers. This section includes the design process and concept design. The final design of the new OS Aqua station will be available at the end of WP5: Design of offshore marine aquaculture station, and it will be provided in a separate document.

3.1 Design considerations and constraints

The design considerations were the following:

1. Suitable to depths 100m-200m.
2. Able to withstand high-energy environments.
3. Able to be constructed and maintained in Eastern Mediterranean shipyards.
4. Able to carry automatization and monitoring systems to reduce operational costs and early detect or prevent accidents or criminal activity.
5. The cage design needs to secure the well-being of the fish. The net volume needs to remain constant with minor depth variation.
6. Potential of being power autonomous using photovoltaics.
7. Can hold a certain amount of feed to eliminate the need for daily trips.
8. Movable either with its own engine or can be pulled by tugboats.
9. It should have a maximum fish population and yield.
10. Easy to maintain and repair.
11. Easy harvesting.

3.2 Concept design, initial calculations of yield, and refinements

After extensive deliberation within the consortium, the following concept design has been generated. The concept draws from the strengths of ship-shaped designs with a rigid frame to sustain harsh weather conditions. However, the design is scaled down to reduce the level of investment required and facilitate early adoption. Additionally, the design draws ideas from submersible designs. In this design, the buoyancy change is used to bring the facility to the surface and facilitate cleaning, maintenance, and transportation. The concept satisfies the above criteria in the following way

1. Suitable to depths 100m-200m.

The ship-shaped design allows the cage to be placed in the open sea and be moored in the required depth range. However, the cost of mooring needs to be defined.

2. Able to withstand high energy environments

The rigid structure will be designed by marine engineers for high-energy environments. There is a possibility of single mooring that will allow for weather vanning.

3. Able to be constructed and maintained in Eastern Mediterranean shipyards.

The size of the cage will be selected based on knowledge of the size of the facilities of local shipyards and is decided in consultation with local service providers.

4. Able to carry automatization and monitoring systems to reduce operational costs and early detect or prevent accidents or criminal activity.

A platform on top of the cage will be able to hold electronic equipment and hardware for monitoring and feeding automatization.

5. The cage design needs to secure the well-being of the fish. The net volume needs to remain constant with minor depth variation.

The rigid frame allows securing nearly constant shaped nets.

6. Potential of being power autonomous using photovoltaics.

As mentioned above, the platform at the top allows the installation of photovoltaics.

7. Can hold a certain amount of feed to eliminate the need for daily trips.

Similarly, the platform will allow the storage of some quantities of feed.

8. Movable either with its own engine or can be pulled by tugboats.

The ship-shaped motion and buoyancy adaptation facilitates motion.

9. It should have a maximum fish population and yield.

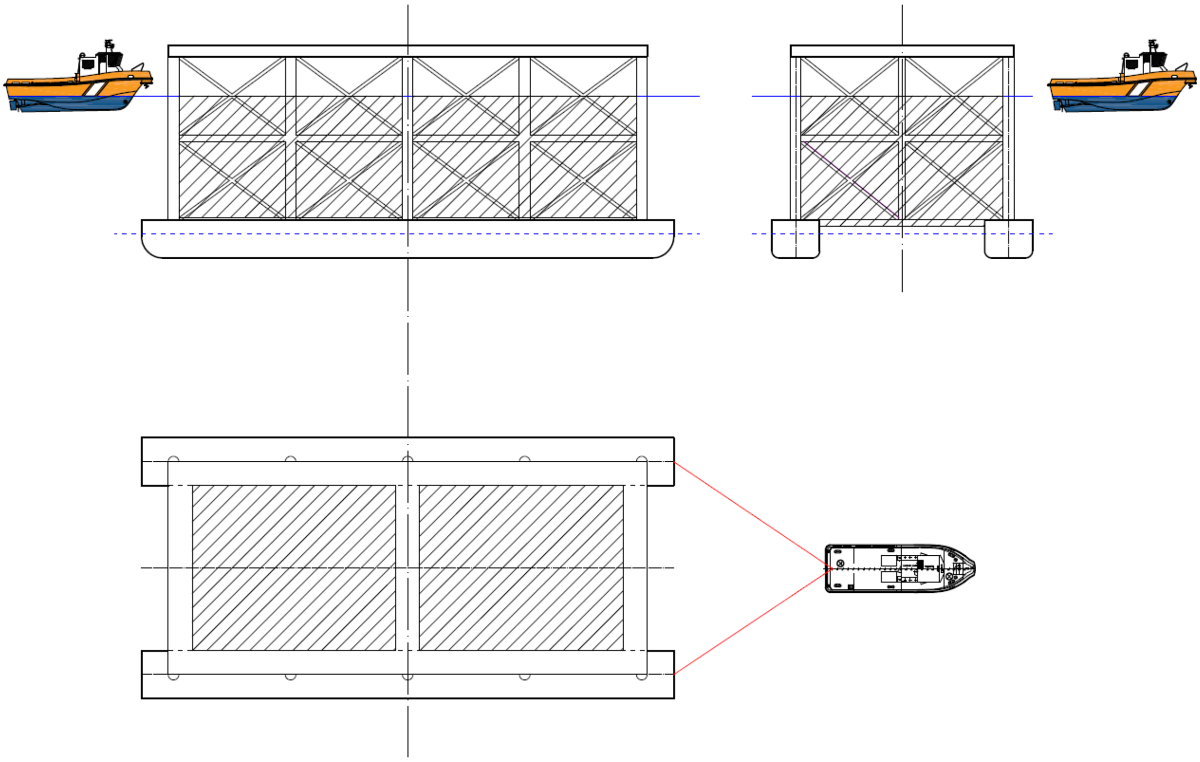
The nets inside the structure can be placed adjacently in an octagonal concept to increase the size of the internal area.

10. Easy to maintain and repair.

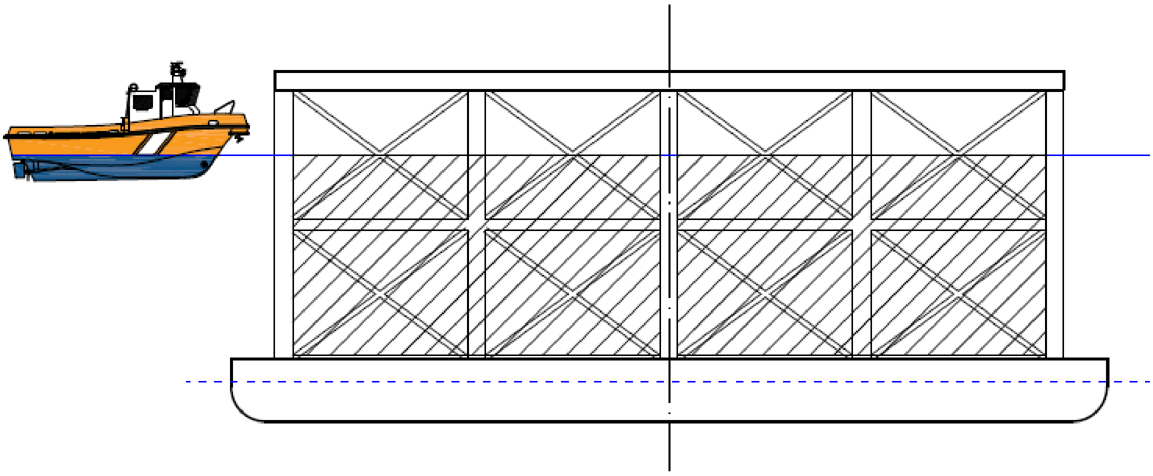
Surfacing the structure facilitates inspection and maintenance.

11. Easy harvesting.

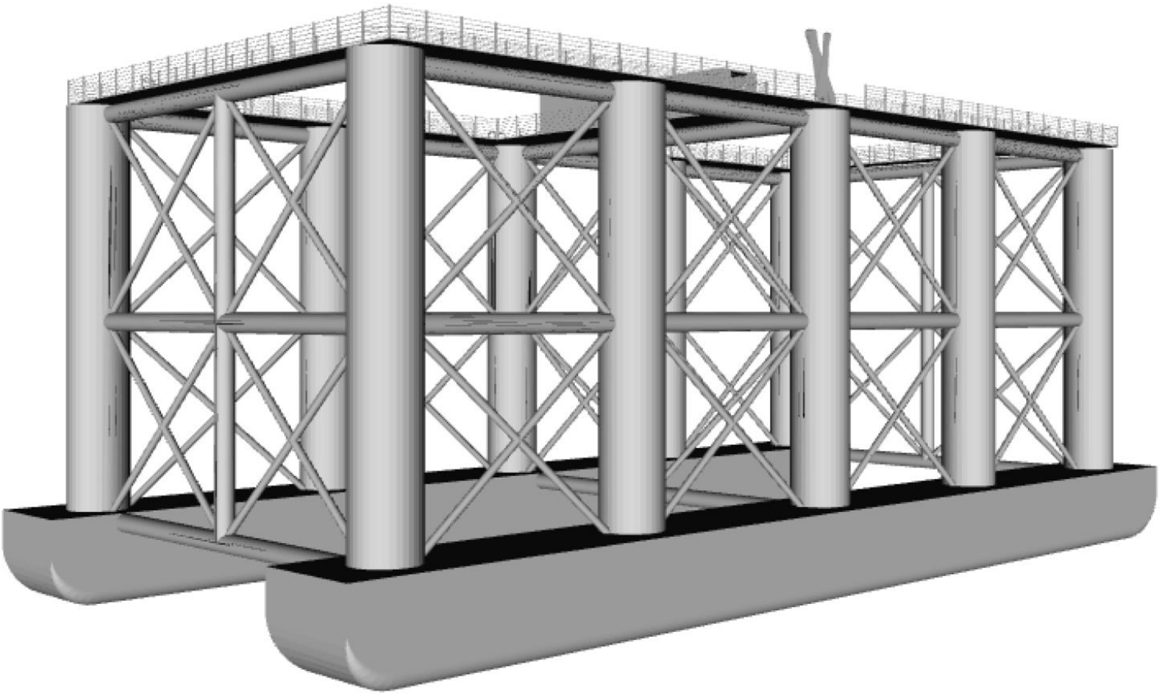
The design allows service vehicle proximity or use of own crane for harvesting.



Concept design from three different viewpoints



Enlarged view from the side indicating the water lines when submerged (solid blue line) and the water level when in the surface (doted blue line).



Three-dimensional representation of the conceptual design.

3.3 Calculations of yield

The new catamaran type of design can accommodate a number of production options, depending on the fish species, and can serve various production scenarios. The system can be combined with nearshore marine aquaculture operations and transfer of young fish at a stage of 10 gr to more than 50 gr for the on-growing period offshore and then move again to the near shore facilities for harvesting and avoidance of issues of rigor mortis due to the long-distance until the fish packaging and fish processing units. Alternatively, the fish can grow as in the nearshore installations. Rectangular cages must be used to maximize the utilization of space, although rectangular cages were replaced from the nineties by cylindrical cages (Theodorou, 2002) by the mariculture industry. Some authors report that the circular shape is found to be more suitable as this shape makes the most efficient use of materials and thus reduces the costs per unit volume. In contrast, observations made on the swimming behavior of fish suggest that circular shapes in a plane area are better in terms of utilization of space as corners of other shapes (rectangular, square, and octagonal) are not properly utilized by the stocked fish in the cage (Das et al., 2016). Nevertheless, many offshore operations do not have cylindroconical shapes and although such shapes can be accommodated in the new design, this would substantially reduce the volume of the cage. This remains to be further tested in the future. For all scenarios, other equipment/facilities that may be required to be fitted onboard include an automated feeding system and control room of sensors and other automation. The installation of a crane is possible but would increase the cost.

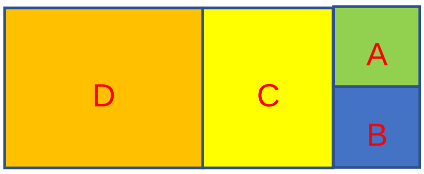
Below four production scenarios are examined, two for a 50 m length structure and two for a 60 m long structure. The production is measured in Tonnes per Cycle. A cycle is defined to include the complete growth period of the dish that depends on the type of fish.

Scenario 1 (50 m length structure): Stocking of 2 gr fish directly in the catamaran-like design.

The structure has dimensions of 50 m length and 20 meters width.

It can accommodate two cages of 490 m^3 (A&B), one cage of 3,000m^3 (C), one cage of 6,720m^3 (D) (10,700 m^3 overall volume) that can support the production of 165 tonnes per year.

Estimated volume/weight of fish food to be kept on board per structure: 8,250 kgr (5 days minimum autonomy without daily service from the land).



CAGES	1,0	1,0	1,0	1,0
	Small A	Small B	Intermediate C	Large D
Size (LxWxD)	7x10x7	7x10x7	15x20x10	28x20x12
m^3	490	490	3,000	6,720
Depth (m)	7.0	7.0	10.0	12.0

Stage 1. We stock the 2 two small cages A and B, with 2 gr fish.

Stage 2. After three months, we grade the larger fish to the intermediate cage C of 3.000 m^3 and the smaller to cage B.

Stage 3. After four months, fish from cage C is transferred to cage D of 6,720 $m^{3,}$ and fish from cage B is transferred to cage C.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
		1	1	1	1		1	1	1	1	1	1	1	1	1	1	1						
		1	1	1	1		1	1	1	1	1	1	1	1	1	1	1						
															1	1	1	1	1	1	1	1	1
															1	1	1	1	1	1	1	1	1

		Volumes	No. of cages	
	Small	490,00	2	980.00
	Intermediate	3.000,00	1	3,000.00
	Large	6.720,00	1	6,720.00
			Total volume =	10,700.00

With this configuration, from one such unit of (50 m length) about 165 tonnes of fish (seabass and seabream) can be cultivated.

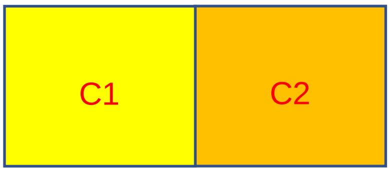
Scenario 2 (50 m length structure): Stocking of 50 gr fish directly in the catamaran-like design (2-50 gr and harvesting operations to be done from near shore associated cage farms).

2 cages of 6,000m^3 (12,000 m^3 overall volume)

Production of 200 tonnes.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
		1	1	1	1	1	1	1	1	1	1	1	1										
					1	1	1	1	1	1	1	1	1	1	1	1							
														1	1	1	1	1	1	1	1	1	1
																	1	1	1	1	1	1	1

Estimated volume/weight of fish food to be kept on board per structure: 10,150kgr (5 days minimum autonomy without daily service from the land).



CAGES	1,0	1,0
	C1	C2
Size (LxWxD)	25x20x12	25x20x12
m^3	6,000	6,000
Depth (m)	12.0	12.0

Stage 1. We stock one C cage with fish of 50 gr.

Stage 2. After four months, we grade the larger fish to one cage C of 6,000 m^3 and the smaller to the other cage.

Stage 3. During harvesting time, fish from cage C is transferred to near shore cages for fasting and harvesting.

Like this, from one such unit of (50 m length) can be cultivated about 200 tonnes of fish(seabass and seabream).

Scenario 3 (60 m length structure): Stocking of 2 gr fish directly in the catamaran-like design.

2 cages of 700 m^3, 1 cage of 4,000m^3, 1 cage of 7,200m^3 (12,600 m^3 overall volume),

Production of 188.0 Tn.

Estimated volume/weight of fish food to be kept on board per structure: 9,430 kgr (5 days minimum autonomy without daily service from the land).

Scenario 4 (60 m length structure): Stocking of 50 gr fish directly in the catamaran-like design. (2-50 g and harvesting operations to be done from near shore associated cage farms).

2 cages of 7,200m^3 (14,400 m^3 overall volume)

Production of 250 Tn.

Estimated volume/weight of fish food to be kept on board per structure: 12,500 kgr (5 days minimum autonomy without daily service from the land).

Number of individual pens, if any, to be included in the catamaran

From the calculations above, from 2 to 4 pens per catamaran will be needed.

If we need to go for production volumes of **2,000 Tn**, the following table summarises the number of the structures needed.

The following table summarises the number of the structures needed and sea surface requirements for production volumes of **2,000 Tn.**

	Tonnes	Number of structures needed	Surface needed (120 m. depth)	Surface needed (160 m. depth)	Surface needed (200 m. depth)
Scenario 1 (50 m length structure)	165	12 structures, 1,980 Tn	0.31 Km^2	0.55 Km^2	0.85 Km^2
Scenario 2 (50 m length structure)	200	10 structures, 2,000 Tn	0.26 Km^2	0.46 Km^2	0.71 Km^2
Scenario 3 (60 m length structure)	188.6	10 structures, 1,886 Tn	0.29 Km^2	0.50 Km^2	0.76 Km^2
Scenario 4 (60 m length structure)	250	8 structures, 2,000 Tn	0.23 Km^2	0.40 Km^2	0.61 Km^2

The following table summarises the number of structures needed and sea surface requirements for production volumes of **3,000 Tn**.

	Tonnes per Year	Number of structures needed	Surface needed (120 m. depth)	Surface needed (160 m. depth)	Surface needed (200 m. depth)
Scenario 1 (50 m length structure)	165	18 structures, 2,970 Tn	0.46 Km^2	0.82 Km^2	1.28 Km^2
Scenario 2 (50 m length structure)	200	16 structures, 3,200 Tn	0.41 Km^2	0.73 Km^2	1.14 Km^2
Scenario 3 (60 m length structure)	188.6	16 structures, 3,018 Tn	0.46 Km^2	0.80 Km^2	1.22 Km^2
Scenario 4 (60 m length structure)	250	12 structures, 3,000 Tn	0.35 Km^2	0.60 Km^2	0.92 Km^2

The following table summarises the number of structures needed and sea surface requirements for production volumes of **5,000 Tn**.

	Tonnes per Year	**Number of structures needed**	**Surface needed (120 m. depth)**	**Surface needed (160 m. depth)**	**Surface needed (200 m. depth)**
Scenario 1 (50 m length structure)	165	30 structures, 4,950 Tn	0.77 Km^2	1.36 Km^2	2.13 Km^2
Scenario 2 (50 m length structure)	200	24 structures, 4,800 Tn	0.61 Km^2	1.09 Km^2	1.71 Km^2
Scenario 3 (60 m length structure)	188.6	26 structures, 4,904 Tn	0.75 Km^2	1.30 Km^2	2.00 Km^2
Scenario 4 (60 m length structure)	250	20 structures, 5,000 Tn	0.58 Km^2	1.00 Km^2	1.53 Km^2

3.4 Concept evaluation

The benefits and possible drawbacks of the design are summarized as follows.

- Placing a platform on the top part of the cage allows the possibility to have storage space that can be used for equipment and feed storage. This reduces the cost of frequent trips to the cages for feeding. A crane can also be fitted for harvesting. Therefore, the platform should not cover the entire top area of the cage to allow access for harvesting. Additionally, feeding automation and surveillance equipment can be added. The possible drawbacks are the increase in the weight and the shade provided to the fish. The alternative is to have vessels carry the food and storage in a separate vessel that serves multiple cages. The financial analysis should cover both scenarios.
- The design is raised above water and transported easily with the maintenance done in Cyprus, increasing local work positions.
- The design is innovative and can be used as a research platform for testing IoT and renewable energy technologies. However, the initial investment will be high, and the venture will be riskier until tested and validated.
- The design is modular, which means that more cages can be placed in the same area.
- The rigid design will provide for resilience in harsh weather. However, there is a concern that the vertical motion of nets will cause motion sickness to fish and decrease the size of the net. To address this concern, the net will be fastened to the steel structure (top, bottom, and sides) in such a way that the volume does not change, or the net will be free below the structure and weighted with blocks, just like the traditional nets. The net could also be made higher than the steel structure. The vertical motion is presently calculated to be limited to 1m (to be calculated based on final designs).
- The concept design has a cuboid shape which facilitates both design and construction. However, it was expressed that pens are best to be round because of the circular motion of the fish and have the minimum surface area/volume ratio, minimizing the size and cost of the net. The cuboid structure could be separated into cubes hosting octagonal pens that will keep the volume of fish as high as possible in respect to the investment. The length of the structure could also be modified to add small pens that can host fishlings.
- The mooring design comes with many options that need to be carefully assessed. Single mooring allows for weather vanning and increases resilience. Moreover, waste is dispersed over wider areas. However, the rotation reduces the number of cages that can be placed close by. Therefore, the financial sustainability with single mooring is questioned. Multiple mooring can instead be used per cage. There is an option of common mooring. However, for common mooring, the dynamics of the cages need to be investigated and the option carries a higher risk.
- The catamaran design will require ballast water treatment and antifouling. Other submersible designs, however, may require this service which necessarily increases the cost.

4 Conclusion and Recommendation

This section provides a conclusion on the outcome of the survey of aquacultural technologies that produced a refinement of the selection of technologies and the concept of a new technology that is suitable to the Eastern Mediterranean. The outcome is a recommendation for which technologies should be included in the financial analysis of WP7: "Financial and Legal Frameworks."

The use of existing coastal sea technologies, combined with suitable mooring could offer a low-cost option for open sea aquaculture in Cyprus. The local know-how would assist in the ease of operations and the application of years of experience in coastal aquaculture to open sea operations. This would allow for an easier transition to open sea systems especially for local companies interested in increasing their portfolio. In addition, the majority of areas considered (WP4) are at relatively low energy systems with wave action comparable to coastal locations where such cages are established.**In terms of existing open sea technologies, the most suitable technologies for the Eastern Mediterranean were the relatively light structures provided by INNOVASEA and Badinotti Group.** These technologies are more similar in size, operation, and maintenance requirements to the conventional cages currently used by local aquaculture producers. Therefore, it is expected that skills and procedures used by local companies will facilitate the early adoption of these technologies for open sea aquaculture. Larger rigid structures may represent a significant change to the business model and operational procedures of local producers. Moreover, even in the availability of a large investment, the currently accessible market will not be able to absorb the yield. These factors will cause a delay in adoption and increase the risk of the investment.

In terms of the new technology, the consortium has combined aspects of existing aquaculture technologies to create a design concept that is suitable to the Eastern Mediterranean in terms of size, maintainability, and scalability, that aspires, through further analysis done by the end of the work package, to prove cost-effective and profitable. The new design is based on the needs and capabilities of Eastern Mediterranean countries with the possibility to be used on a global level in environments that are similar to those of the Eastern Mediterranean. Specifically, the size, type, and material is selected in such a way that allows local expertise of marine engineering and shipbuilding to be used, considering the size of local shipyards, will be enough to develop these stations and even export them abroad. Therefore, the goals of the funding program to stimulate economic growth by providing new jobs and increasing imports will be attained and further strengthened.

As a final remark, the selection of technologies included in this deliverable is a major contribution but not sufficient to complete the financial framework. The rest of the information will be complemented by other work packages that provide the type of fish, the carrying capacity of the selected area, the calculation of yield, and the market analysis.

5 References

Antonucci, F., & Costa, C. (2020). Precision aquaculture: a short review on engineering innovations. Aquaculture International, 28(1), 41-57.

Benetti, D. D., Benetti, G. I., Rivera, J. A., Sardenberg, B., & O'Hanlon, B. (2010). Site selection criteria for open ocean aquaculture. Marine Technology Society Journal, 44(3), 22-35.

Beveridge, M. C. (2008). Cage aquaculture (Vol. 5). John Wiley & Sons.

Bi, C. W., Zhao, Y. P., Dong, G. H., Xu, T. J., & Gui, F. K. (2017). Numerical study on wave attenuation inside and around a square array of biofouled net cages. Aquacultural Engineering, 78, 180–189.

Brenden, Travis O., Brian R. Murphy, Steve Manos, and Chris S. Vandergoot. "A submerged cage designed for aquatic research." North American Journal of aquaculture 61, no. 4 (1999): 359-362.

Buck, B. H., & Buchholz, C. M. (2004). The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. Journal of Applied Phycology, 16(5), 355–368.

Buck, B. H., & Langan, R. (2020). Aquaculture Perspective of Multi-Use Sites in the Open Ocean: The Untapped Potential for Marine Resources in the Anthropocene. Saint Philip Street Press.

Cardia, F., & Lovatelli, A. (2016). Key Project Achievements in the Kingdom of Saudi Arabia: Latest FAO/KSA Aquaculture Unilateral Trust Fund Project Recently Terminated. FAO Aquaculture Newsletter, (55), 33.

Chambers, M. D., & Howell, W. H. (2006). Preliminary information on cod and haddock production in submerged cages off the coast of New Hampshire, USA. ICES Journal of Marine Science, 63(2), 385-392.

Chu, Y. I., Chien Ming Wang, Jeong Cheol Park, and Pål Furset Lader. "Review of cage and containment tank designs for offshore fish farming." Aquaculture 519 (2020): 734928.

Clemence, M., Hurd, F., Lahr, H., Mahdi, A., Tresham, A., & Young, J. (2011). Spatial Planning and Bio-Economic Analysis for Offshore Shrimp Aquaculture in Northwestern Mexico. University of California, Santa Barbara, Santa Barbara, California (Master's thesis).

Costa-Pierce, B. A., & Bridger, C. J. (2002). The role of marine aquaculture facilities as habitats and ecosystems. Responsible marine aquaculture, 105-144.

DeCew, J., I. Tsukrov, A. Risso, M. R. Swift, and B. Celikkol. "Modeling of dynamic behavior of a single-point moored submersible fish cage under currents." Aquacultural Engineering 43, no. 2 (2010): 38-45.

Dempster, T., Lader, P., Fredheim, A., & Jensen, Ø. (2008). Current induced net deformations in full-scale sea-cages for Atlantic salmon (Salmo salar). Aquacultural Engineering, 38(1), 52-65.

Fredriksson, D. W., DeCew, J., Swift, M., Tsukrov, I., Chambers, M. D., & Celikkol, B. (2004). The design and analysis of a four-cage grid mooring for open ocean aquaculture. Aquacultural Engineering, 32(1), 77–94.

Gansel, L. C., Jensen, Ø., Lien, E., & Endresen, P. C. (2014). Forces on Nets With Bending Stiffness—An Experimental Study on the Effects of Flow Speed and Angle of Attack. Journal of Offshore Mechanics and Arctic Engineering, 136(4).

Gratacap, R. L., Wargelius, A., Edvardsen, R. B., & Houston, R. D. (2019). Potential of genome editing to improve aquaculture breeding and production. Trends in Genetics, 35(9), 672-684.

He, Z., Faltinsen, O. M., Fredheim, A., & Kristiansen, T. (2018). The influence of fish on the mooring loads of a floating net cage. Journal of Fluids and Structures, 76, 384–395.

Helsley, C. E., & Kim, J. W. (2005). Mixing downstream of a submerged fish cage: a numerical study. IEEE Journal of Oceanic Engineering, 30(1), 12-19.

Høiland, A. V. (2017). Dynamic analysis of a vessel-shaped fish farm for open sea (Master's thesis, University of Stavanger, Norway).

Holm, P., Buck, B. H., & Langan, R. (2017). Introduction: new approaches to sustainable offshore food production and the development of offshore platforms. In Aquaculture Perspective of Multi-Use Sites in the Open Ocean (pp. 1-20). Springer, Cham.

Holm, P., Buck, B. H., Langan, R., Nevejan, N., Wille, M., Chambers, M. D., ... & van der Putten, S. (2017). Aquaculture Perspective of Multi-Use Sites in the Open Ocean.

Houston, R. D., Bean, T. P., Macqueen, D. J., Gundappa, M. K., Jin, Y. H., Jenkins, T. L., ... & Robledo, D. (2020). Harnessing genomics to fast-track genetic improvement in aquaculture. Nature Reviews Genetics, 21(7), 389-409.

Huang, C. C., & Pan, J. Y. (2010). Mooring line fatigue: A risk analysis for an SPM cage system. Aquacultural engineering, 42(1), 8-16.

Huang, X. H., Liu, H. Y., Hu, Y., Yuan, T. P., Tao, Q. Y., Wang, S. M., & Liu, Z. X. (2020). Hydrodynamic performance of a semi-submersible offshore fish farm with a single point mooring system in pure waves and current. Aquacultural Engineering, 90, 102075.

Tidwell, J. H. (2012). Aquaculture production systems. John Wiley & Sons.

Huguenin, J. E. (1997). The design, operations and economics of cage culture systems. Aquacultural Engineering, 16(3), 167-203.

Kamaruidzaman, N. S., & Rahmat, S. N. (2020, May). Water Monitoring System Embedded with Internet of Things (IoT) Device: A Review. In IOP Conference Series: Earth and Environmental Science (Vol. 498, No. 1, p. 012068). IOP Publishing.

Kankainen. M, Rune Mikalsen (2014)Offshore fish farm investment and competitiveness in the Baltic sea Report number: 2 Affiliation: Report of Aquabest project; http://www.aquabestproject.eu/reports.aspx Project: Aquabest

Kapetsky. J., J. Aguilar-Manjarrez and J. Jenness. (2013). A global assessment of potential for offshore mariculture development from a spatial perspective. FAO Fisheries and Aquaculture Technical Paper No. 549. FAO, Rome. 181 p

Klebert, P., Patursson, Y., Endresen, P. C., Rundtop, P., Birkevold, J., & Rasmussen, H. W. (2015). Three-dimensional deformation of a large circular flexible sea cage in high currents: Field experiment and modeling. Ocean Engineering, 104, 511–520.

Korsøen, Øyvind J., Tim Dempster, Per Gunnar Fjelldal, Frode Oppedal, and Tore S. Kristiansen. "Long-term culture of Atlantic salmon (Salmo salar L.) in submerged cages during winter affects behaviour, growth and condition." Aquaculture 296, no. 3-4 (2009): 373-381.

Kruusmaa, M., R. Gkliva, J. A. Tuhtan, A. Tuvikene, and J. A. Alfredsen. "Salmon behavioural response to robots in an aquaculture sea cage." Royal Society open science 7, no. 3 (2020): 191220.

Langan, R. (2012). Ocean cage culture. Aquaculture production systems, 135-157.Loverich, GF, Gace, L., 1997. The effect of currents and waves on several classes of offshore sea cages. International Conference on Open Ocean Aquaculture'97, Maui, HI, USA, 23 /25 April 1997, pp. 131/144

Lee, D. G., Cha, B. J., Park, S. W., Kwon, M. G., Xu, G. C., & Kim, H. J. (2013). Development of a vision-based automatic vaccine injection system for flatfish. Aquacultural engineering, 54, 78-84.

Leow, Ban Tat, and Hoon Kiang Tan. "Technology-Driven Sustainable Aquaculture for Eco-tourism." In WCFS2019, pp. 209-218. Springer, Singapore, 2020.

Li, L., & Ong, M. C. (2017, June). A preliminary study of a rigid semi-submersible fish farm for open seas. In International Conference on Offshore Mechanics and Arctic Engineering (Vol. 57779, p. V009T12A044). American Society of Mechanical Engineers.

Li, L., Jiang, Z., Wang, J., & Ong, M. C. (2019). Numerical study on the heading misalignment and current velocity reduction of a vessel-shaped offshore fish farm. Journal of Offshore Mechanics and Arctic Engineering, 141(5).

Loverich GF, Gace L (1997) The effects of currents and waves on several classes of offshore sea cages. In: Helsley CE, Open Ocean Aquaculture: Charting the Future of Ocean Farming. University of Hawaii, Maui, Hawaii, USA 131–144.

Mohapatra, S., & Soares, C. G. (2019). Interaction of ocean waves with floating and submerged horizontal flexible structures in three-dimensions. Applied Ocean Research, 83, 136–154.

Ohrem, Sveinung Johan, Eleni Kelasidi, and Nina Bloecher. "Analysis of a novel autonomous underwater robot for s." In 2020 28th Mediterranean Conference on Control and Automation (MED), pp. 1002-1008. IEEE, 2020.

Paspalakis, S., Moirogiorgou, K., Papandroulakis, N., Giakos, G., & Zervakis, M. (2020). Automated fish cage net inspection using image processing techniques. IET Image Processing, 14(10), 2028-2034.

Scott, D. C. B., & Muir, J. F. (2000). Offshore cage systems: A practical overview. Option Mediterraneennes-International Centre for Advanced Mediterranean Agronomic Studies, 79-89.

Shainee, M., Ellingsen, H., Leira, B. and Fredheim, A., (2021). Design theory in offshore fish cage designing.

Shainee, M., Ellingsen, H., Leira, B., & Fredheim, A. (2013b). Design theory in offshore fish cage designing. Aquaculture, 392–395, 134–141.

Svendsen, Eirik, Martin Føre, Finn Økland, Albin Gräns, Richard David Hedger, Jo Arve Alfredsen, Ingebrigt Uglem et al. "Heart rate and swimming activity as stress indicators for Atlantic salmon (Salmo salar)." Aquaculture 531 (2021): 735804.

Takeuchi, Y. (2019). 3d printable hydroponics: A digital fabrication pipeline for soilless plant cultivation. IEEE Access, 7, 35863-35873.

Tsukrov, Igor, Andrew Drach, Judson DeCew, M. Robinson Swift, and Barbaros Celikkol. "Characterization of geometry and normal drag coefficients of copper nets." Ocean Engineering 38, no. 17-18 (2011): 1979-1988.

Yue, G. H., & Wang, L. (2017). Current status of genome sequencing and its applications in aquaculture. Aquaculture, 468, 337-347.

Zenger, K. R., Khatkar, M. S., Jones, D. B., Khalilisamani, N., Jerry, D. R., & Raadsma, H. W. (2019). Genomic selection in aquaculture: application, limitations and opportunities with special reference to marine shrimp and pearl oysters. Frontiers in genetics, 9, 693.

Theodorou A. John (2002). Current and Future Technological Trends of European Seabass-Seabream Culture, Reviews in Fisheries Science, 10:3-4, 529-543, DOI: 10.1080/20026491051776

Biswajith Das, Ritesh Ranjan, Shubhadeep Ghosh, Narasimhulu Sadhu and Vamsi Balla (2016). Engineering aspects of cage design, mooring and net design for open sea cage farming in India. In: Training Manual on Cage Culture of Marine Finfishes. Training Manual Series No. 10 / 2016. Editors Sekar Megarajan, Ritesh Ranjan. ICAR-Visakhapatnam Regional Centre of Central Marine Fisheries Research Institute Visakhapatnam, Andhra Pradesh, India Sekar Megarajan, Ritesh Ranjan Biji Xavier & Shubhadeep Ghosh, 100 pp.