Outline of concepts for aquaculture on floating modular islands

D8.1

Grant Agreement No.	774253
Start date of Project	1 November 2017
Duration of the Project	36 months
Deliverable Number	D8.1
Deliverable Leader	STICHTING WAGENINGEN RESEARCH (WUR)
Dissemination Level	PU
Status	V1.0
Submission Date	04-04-2019
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774253.

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Modification Control

Version #	Date	Author	Organisation
V0.1	14-03-2018	R.G. Jak	WUR
V0.2	20-07-2018	R.G. Jak	WUR
V0.3	30-10-2018	S. Matthes	GICON
V0.4	9-11-2018	M. Poelman, R.G. Jak	WUR
V0.5	12-12-2018	K. Fagerland E. Schram M. Poelman	VALFoU WUR WUR
V0.6	21-02-2018	R.G. Jak	WUR
V0.7	22-03-2019	M. Poelman	WUR
V1.0	04-04-2019	R.G. Jak	WUR

Release Approval

Name	Role	Date
R.G. Jak	WP Leader	03-04-2019
W. Murtinu	Project Office	04-04-2019
M. Flikkema	Project Coordinator	04-04-2019

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Executive Summary

This report describes concepts for aquaculture that can be considered for application at floating modules as being developed in the Space@Sea project. It provides an inventory of the culturing options of a range of organisms; i.e. fish, shellfish (mussels), seaweeds and microalgae. A general description is provided for state-of-the-art systems for culturing these organisms. In relation to the use of floating modules, several options are available for the positioning of culturing systems. They can be positioned on deck of the modules, placed under the models or in between them. Also “open” modules specifically designed for aquaculture could be considered. In addition, the modules could serve as an anchoring point for culture systems placed on the outside of modules. Finally, culture systems may be anchored independent, where modules are only used to deliver services, including work space. For each relevant combination of organism-culture system-position a factsheet is provided giving a short description, the main characteristics and requirements and a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis. Possible combinations are discussed and it is proposed to perform a multi-criteria analysis to select the most promising options for further elaboration with respect to the application at/with floating modules and in combination with other functions of floating islands, and combinations.

1. Introduction

1.1 Space@Sea

Space@Sea sets out to provide sustainable and affordable workspace at sea by developing a standardised and cost efficient modular island with low ecological impact. The consortium consists of a strong collaboration between 17 partners spread throughout Europe. Space@Sea will develop and demonstrate a modular floating island approach including four example applications which will result in three business cases to be further detailed.

Aquaculture is considered as one of the application options for multi-use platforms. Combining several functions may not only reduce costs but could also enable new technologies to be applied at sea. In this report an inventory of possible aquaculture options is made, in order to select the most promising options for which further business cases will be developed.

1.2 Farming@Sea

The workpackage on Farming@Sea explores the aquaculture options that benefit from the modular floaters that are designed for Space@Sea. We consider culturing of fish, mussels, seaweeds and microalgae in different type of culture systems in relation to the floating modules. In addition to beneficial aspects of floating modules, we will consider the benefits and constraints of offshore conditions for culture technologies and the target species.

The aim of this report is to describe possible concepts for aquaculture which can be applied on floating modular island at the open sea.

1.3 Concepts for aquaculture at modular floating constructions

Task 8.2 aims to define promising concepts for offshore aquaculture for application at modular structures, considering seaweed, mussels, microalgae, fish, and Integrated multi-trophic aquaculture (IMTA).
For microalgae the main focus is the development of a novel PBR (photobioreactor) concept with its corresponding adaptive control technology. This deliverable D8.1 provides an outline of concepts that can be applied on floating modular island.

In the following chapters an introduction to the various options for aquaculture are briefly introduced, taking into account current practices and recent developments.

Thereafter, the application of aquaculture in relation to floating modules is considered. For 26 options factsheets are developed (all provided in the Annex) including a description of the system, the main requirements and characteristics and a SWOT[1] analysis where benefits and constraints are summarized.

[1] Strengths, Weaknesses, Opportunities and Threats

2. Introduction to aquaculture practices and developments

This chapter introduces current aquaculture practices and developments that are taking place in the sector.

2.1 Aquaculture in Europe

2.1.1 Current production

In Europe, aquaculture production has remained relatively constant in the last years. In 2015, the total output of European aquaculture was 3.0 million tonnes, of which the majority (2.4 million tonnes) was marine production (FAO FishStat). The marine aquaculture production was represented almost exclusively by fish production (about 1.8 million tonnes) and bivalve production (about 598 thousand tonnes) (FEAP 2016; FAO 2017). Culture of other marine organisms like macroalgae and crustaceans is negligible in Europe The most important species (freshwater and marine) reared in Europe in 2015 are Atlantic salmon (1.6 million tonnes per year), mussels (497 thousand tonnes per year), rainbow trout (290 thousand tonnes per year), common carp (154 thousand tonnes per year), Pacific cupped oyster (89 thousand tonnes per year), gilthead sea bream (79 thousand tonnes per year) and European sea bass (68 thousand tonnes per year) (FAO 2017). Within Europe, the largest producers of marine aquaculture products are Norway (1.4 million tonnes, mainly Atlantic salmon), Spain (271 thousand tonnes per year), United Kingdom (196 thousand tonnes per year), France (161 thousand tonnes per year) and Greece (103 thousand tonnes per year). With regard to the aquaculture of marine bivalves in the different countries, Mediterranean mussels accounted for 83.0% of the marine aquaculture in Spain whereas in France, the largest volumes were produced by Pacific cupped oyster (46.6%), blue mussel (37.9%) and Mediterranean mussel (8.8%). The growth of marine Aquaculture production in Europe is mainly caused by the increase in fish culture (Atlantic salmon) since 1985–1990 . The production of marine bivalves by European aquaculture is decreasing from an average production of 661 thousand tonnes per year in the period 1995–1999 to an average of 560 thousand tonnes per year in the period 2010–2014.

2.1.2 Aquaculture in future scenarios

A growing human population, 9.7 billion by 2050 according to United Nations estimates (Béné et al., 2016; SAPEA, 2017), and the expectations of citizens from an increasingly prosperous developing world will intensify the global demand for food (European Commission Scientific Advice Mechanism, 2016). Not only will there be many more people, but today's nutritional challenges (hunger, undernutrition and micronutrient deficiencies), coupled with the expectations of citizens in an increasingly prosperous world, where people are eating more meat and fish in their diets, will intensify the global demand for food and biomass. Given current trends, total food demand is projected to increase by 60% by 2050, according to the Food and Agriculture Organisation of the UN (SAPEA, 2017). This will push conversion of land to crops and pasture as well as putting pressure on freshwater resources that are already in many cases over-exploited and threatened by global warming (European Commission Scientific Advice Mechanism, 2016).

Any additional biomass demand other than for food, such as for bioenergy or feed adds further pressure and their expanded use should be carefully investigated (Conijn et al., 2018). According to the EU Blue Growth strategy (2012) further clearing of forests or draining of wetland or depletion of marine resources and ecosystems will deprive future generations of the benefits they provide. Therefore, we need to look how the ocean, which represents 71% of the planet can deliver human necessities such as food and energy in a way that is more sustainable (Commission of the European Communities, 2012). Following the EU Food 2030 strategy (2016) this should include (next to developments in the sustainable use of land and soil) the sustainable use of marine waters and biodiversity as providers of ecosystem services upon which food production relies (European Commission, 2016).

In Europe currently this consideration on how to sustainably harvest more food from the oceans (European Commission Scientific Advice Mechanism, 2017; SAPEA, 2017) is reflected in such initiatives as the 2012 Blue Growth strategy (Commission of the European Communities, 2012; Bell et al., 2017), the 2014 communication on innovation in the blue economy (Commission of the European Communities, 2014), the 2016 FOOD 2030 initiative (European Commission, 2016a) the 2016 Ocean Governance initiative (European Commission, 2016b) and the initiative of the EU College of Commissioners, led by Commissioner Vella, to request scientific advice in the area of food and biomass from the oceans (European Commission, 2017). Hence there is the necessity and the political will to investigate "How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits" (European Commission Scientific Advice Mechanism, 2016). Next to this political will, there is of course also the necessity to develop the science underpinning and enabling this development.

On land, space and water are becoming scarce commodities. Yet our planet consists for 71% of water, with 95% of our water reserve in our oceans and seas. Today we are not using this potential to its fullest. The "green evolution" enabled us to feed the current world-population; a "blue revolution" is needed to feed the world by 2050. This is a revolution as utilising our ocean resources more we need a springboard to develop the necessary innovations rather than an incremental development from current practices.

Main Drivers for an increased use of the ocean's resources are hence addressing the need for food (and feed), drinking water and renewable energy. A hinterlying driver, when using the oceans, is addressing the governance of this development. We have to raise the question of how to address the innovation needed to realise this blue revolution. This raises issues of who the relevant innovators in this process will be. Because on the one hand the development of food, energy and water are today domains of different players, between whom little to no interaction takes place. On the other hand it raises the issue of Ocean Governance: where in general coastal zone's and EEZs are under national jurisdiction, the international waters and deep seas lack adequate governance institutions.

Also when we will use the seas and oceans more intensively we have to take into account that today these waters are already in use by other users such as fishermen, aquaculturists, shippers, oil and gas producers, the tourist sector, gravel extraction, windfarms and other renewable energy producers. Traditionally our coasts and deltas host many people of whom quite a substantial part make their living already today from sea related activities. This entails employment and income but also food security, cultural values and vital communities. New and added uses have to fit in into this puzzle.

Although vast parts of our oceans are not largely in use today, there is already substantial competition for sea space. Especially in the near shore and coastal zone competition can be fierce, due to the availability of resources (such as fish) or the relative short distance to port which for example results in lower costs of cabling in case of energy production and a relative short travel time between port and aquaculture facilities.

An optimal use of ocean space hence takes into account that the ocean value chain will as much as possible integrate different uses in a single location (for example seaweed and shellfish production in between wind farm pylons). In addition, the ocean value chains take a global perspective in which at a global level sustainability is addressed in circular production processes. In this, regional differences are taken into account. For example towards 2050 the population of the African continent is expected to double and today for example the aquaculture potential is not fully explored. Europe is facing an aging population and is a net fish importer.

Production at sea of course has to be sustainable. But as we have a sincere lack of knowledge about the marine ecosystem, especially considering the deep sea and high seas, but also in the near shore areas, and all oceans are inter-connected, circularity and zero-waste concepts need to guide the development of the ocean value chains.

2.2 Fish culturing

Currently, the major part of fish farming takes place in cages that are deployed in inshore of nearshore waters of Norway and the Mediterranean sea (France, Italy, Spain, Turkey). Concerns are raised on the interaction with the natural environment, including the release of fish wastes (nutrients, feed, biocides), and the risk of escapes of cultured species and diseases. In addition, dense culturing in the coastal environment increases the risk of infections by parasites such al fish lice. Ongoing developments are aiming to reduce the environmental impacts and to increase fish welfare, resulting in a transition to closed systems and/or offshore environments.

2.2.1 Developments in Norway

The changes happening in Norwegian aquaculture practices are taking place at a very high rate, making it only possible to make predictions for the next 2-3 years. It is difficult to define the expected future changes in aquaculture practices during the next 5-10 years.

To illustrate the development we can look back at fish farming in the 1970-80, some 40 years ago. A typical cage back then was made of wood with a circumference of 40 meters and 5 meters deep nets and with 5-7000 fish per cage. The low degree of technology resulted in a high requirement of manual work. There was very little focus on interaction with the environment. Often the main criteria for selecting a location was the availability of a bay that gave shelter to wind and waves. Production time in sea for salmon was usually 18-24 months, with 60 grams smolt set at sea. There was little focus on both fish welfare and on safety issues in the industry.

Fish farming today on an ordinary site is completely different. The units have grown in size, with a common circumference of 160 m, with higher density of fish and more advanced and specialized technology. For example, decentralized feeding stations can operate 5 sites and 36 cages (approximately 10.000 tons of salmon). The industry is more professionalized in all aspects. The high focus on fish welfare has resulted in that most companies have their own veterinarian/fish biologist employed. Research and development is a part of the strategy and daily operations in all the companies result in a high rate development of the industry. The main drivers for the current development is the focus on the environment and fish welfare.

The environmental focus in the industry has resulted in inventions that replace chemicals and antibiotics with more environmentally friendly alternatives for the handling of the problem of sea lice. Mechanic fleets which de-lice the fish using high pressure water or use of fresh water treatment in well boats are examples of this. Cleaner-fish as wrasse and lumpfish which eat sea lice are also common use.

The Norwegian government has been stimulating the companies to apply for development licenses based on new ways of cage construction. This has resulted in a lot of projects on possible future cage constructions. During the temporary arrangement of 2 years from November 2015 to November 2017 the government received 104 applications in total where of 53 have got refused and until now 8 have been granted.

A challenge and focus in all the projects is developing solutions that prevent sea lice and developing cage constructions that prevent escaping of fish.

2.2.2 Offshore Cage Culture

The main drivers behind moving aquaculture offshore is to make use of new sea areas combined with solutions to environmental challenges, especially the control of sea lice. By moving the cages out into open sea, it will reduce the exposure to natural occurrence of sea lice, which has lower densities offshore. Two applications are granted in Norway on the development of offshore cages.

Ocean Farming was the first concept realized within Norway's development licenses system by SalMar. The concept is offshore fish farming suitable for water depths of 100 to 300 meters. The giant cage is 68 meters high, has a diameter of 110 meters and has a capacity of 250,000 cubic meters. The cage will initially hold one million fish of 250 grams. The concept has integrated underwater sensors introducing “big data” to aquaculture. The project combines advanced marine engineering and marine cybernetics.

Havfarm is under construction and to be realized in 2019. The concept owned by Norwegian salmon farmer Nordlaks, will be able to hold 10,000 tons of fish and is designed for exposed sites that previously couldn’t be exploited. The structure has a bow like a ship, and a closed hull down to a certain depth. The cages can be moved, and the locations can thus be adapted to season variation in weather.

2.2.3 Closed Containment Aquaculture Culture System (CCAS)

The main drivers behind closed containment systems is to produce salmon without influencing the environment. The closed systems collect and recycle waste deposits for use in other renewable products. In closed systems the risk of fish escapes is reduced and the system prevents sea lice. From a fish welfare perspective the absence of sea lice may cause the fish to be subjected to minimum handling. Handling of fish due to de-licing are very critical operations in today’s productions. Challenges in closed concept is keeping the water quality sufficient in the cages.

Closed containment systems in the ocean can play an important role in the aquaculture industry in the future, but it still requires further development. The further research focus on closed cage systems will include a more cost-effective water treatment and how to apply the production into more exposed areas. Three licences have been granted in Norway on the developments of CCAS.

FlexiFarm by Cermaq is a closed containment system based on a tarpaulin-walled cage. The water is pumped into the cage from a depth of 13 meters, below the sea lice layer (8 top meters). It is the world's largest closed cage using flexible walls. The concept will include cost-effective water treatment against infections.

AkvaDesign is a tarpaulin-walled cage. The energy consumption is based entirely on renewable Norwegian hydropower. Circulation of the water within the closed cages helps maintain the health of the salmon and keeps them in motion at all times. To reduce the risk of fish the tarpaulin walls have a double protection system.

Egget Marine Harvest. The concept has not been realized, as they have not been granted the sufficient amount of development licenses as the concept has high development costs as the cage is made of solid walls instead of tarpaulin.

2.2.4 Flow through tank system

Tank based production system inside a building or outdoors with seawater passing through to maintain water quality, high water demand and limited control over conditions. The main advantage of these systems is the supply of clean water. Disadvantages are numerous, including limited control of environmental conditions (important for the growth of fish), and the release of polluted water. For offshore application on floating modules, these systems have no marked advantageous over cage systems or recirculation systems (see below) and are therefore not elaborated in more detail here.

2.2.5 Recirculating Aquaculture System (RAS)

General system description

Recirculating aquaculture systems, usually named by its abbreviation RAS consist of tanks in which the aquatic organisms are housed combined with water treatment facilities. RAS are typically land-based and indoors. Similar to flow through systems and cage systems, fish tanks in RAS require continuous water exchange to maintain sufficient water quality for fish production; the water flow through the fish tank serves to transport oxygen to the fish and to remove fish metabolites. Unlike flow through systems in which water is discharged after single passage through the farm, RAS involve reuse of culture water after internal purification. To this end all designs of RAS remove solid wastes, oxidize ammonia and nitrite, remove carbon dioxide, and aerate or oxygenate the water before returning it to the fish tank. More intensively-stocked systems or systems culturing sensitive species may require additional treatment processes such as fine solids removal, dissolved organics removal, and water disinfection. Irrespective of their exact design, all RAS are mechanically sophisticated and biologically complex compared to flow through tank or cage production systems. Recirculating aquaculture technology can be applied for all stages of aquatic animal production, including brood stocks, hatchery and nursery rearing, grow-out and quarantine holding.

Main processes in RAS and the associated system components

Fish production

Fish production is entirely feed based; within the system there is no natural productivity that sustains fish biomass production. Fish production takes place in tanks. Each RAS consists of multiple tanks to house the different fish batches within the standing stock. During the growth process, fish batches are often sorted by size, split over different tanks multiple times as part of the stock management. Tank size, shape and construction may all very widely within and among RAS to cater the needs of species, live stages and management.

Transport of water

Tank water is continuously replaced at a rate of typically 1 to 5 tank volumes per hour. Tank water replacement transports oxygen to the fish while removing wastes. In RAS the water is recycled between the fish tanks and the water treatment facilities. The designs of the tank, the water inlet and water outlet can be aimed at creating water flow patterns that promote proper water mixing, concentration of solid wastes at the outlet and promote desired swimming activity of the fish. Depending on the RAS design there are one or more water loops. Water is transported by pumping and gravity. Investment costs for pump are a significant part of the total investments in a RAS. Water pumping contributes significantly to the power consumption of the RAS, which is a significant part of the operational costs of a RAS.

Removal of solid wastes

Solid wastes are mostly organic matter originating from fish faeces and uneaten feed. Organic matter needs to be removed from system as its decay consumes oxygen and thereby competes for available oxygen with fish and nitrifying bacteria (see below). Too high levels of suspended materials in the water negatively affect the fish. Removal of solids starts in the fish tank by concentrating it near a tank out flow point. Solids are removed from the water by mechanical filtration (drum or disk filters) or sedimentation in sedimentation tanks or upflow filters. Very fine solids (small particles) may be removed by protein skimmers. Removal of solids is generally the first process step within the water treatment in RAS.

Removal of ammonia

Fish produce ammonia as end product of their protein metabolism. Since fish mainly use proteins as energy source, their nitrogenous waste production is generally high compared to terrestrial animals. Fish excrete ammonia to the water via their gills. As dissolved ammonia is toxic to fish it needs to be removed. Ammonia is removed from the fish by continuously renewing the water in fish tanks. Within RAS ammonia is removed from the water by biological oxidation (nitrification). Generally the nitrifying biofilters contain large surface areas for attached growth of biofilms containing nitrifying bacteria. These filter beds can be fixed in trickling, submerged or rotating biofilters. Alternatively, the filter bed consists of small carriers that are suspended in moving bed bioreactors. In the nitrification process ammonia is converted to less toxic nitrate, with the very toxic nitrite as intermediate product. The capacity (amount of ammonia that can be converted per unit of time) of a properly designed and operated nitrifying biofilter matches the ammonia production of the fish to prevent accumulation of toxic ammonia in the water. Operational conditions such as temperature, salinity, oxygen concentration, pH and concentration of organic matter all affect the nitrification capacity of a biofilter.

Removal of nitrate

Nitrate is formed as end product of the nitrification process (see Removal of ammonia). Nitrate is only toxic to fish at high concentrations and can thus be allowed to accumulate in the system water to high levels. However, to prevent excessive nitrate accumulation to toxic levels, nitrate removal from the system water is necessary. Nitrate accumulation can be controlled by nitrate removal via system water replacement (replacing system water containing nitrate with new water with low(er) nitrate levels, see below). Alternatively, nitrate can be removed by denitrification within the RAS water treatment system. Denitrification is the biological reduction of nitrate to nitrogen gas. The process requires anoxic conditions and a carbon source, which is either added (external) or the organic matter in the solid wastes are used for this (internal). Denitrification reactors are mostly upflow reactors filled with a fixed or suspended bed for attached biofilm growth.

Removal of carbon dioxide

Fish produce carbon dioxide as metabolite and excrete it to the water. In water this carbon dioxide is taken up in the carbonate system. Carbon dioxide production by the fish may thus affect the levels dissolved carbon dioxide, bicarbonate and carbonate in the water as well as the pH, alkalinity and water hardness, all depending on the chemistry and temperature of the receiving water. To prevent toxic effects, excess carbon dioxide should be removed from the water. Just like ammonia, carbon dioxide is removed from the direct environment of the fish by continuously renewing the water in fish tanks. Carbon dioxide is then removed from the water by ‘air-stripping’. The carbon dioxide stripper is essentially a ventilated packed column in a side loop over which the water trickles down. Carbon dioxide is removed from the water as it diffuses to the air phase in the column. In case a trickling filter is used as nitrification filter (see Removal of ammonia) this filter also functions as a carbon dioxide stripper. From all the inorganic carbon components in the carbonate system, only free carbon dioxide can be removed from water by air-stripping. As the inorganic carbon chemistry in seawater is relatively complex while marine RAS are a relatively recent development, carbon dioxide removal from marine RAS is one of the least developed water treatment processes.

pH control

The production of hydrogen ions by the nitrification process leads to acidification of the water. The subsequent drop in pH needs to be counteracted to maintain proper water quality for the fish. The extent to which the pH drops depends on the overall water chemistry and buffering capacity. RAS using water with a high buffering capacity combined with a high system water renewal rate may not need additional measures to keep the pH above threshold levels. In other cases the pH can be controlled by (automated) dosage of sodium hydroxide or sodium bicarbonate.

Disinfection of the water

Disinfection of the water may be applied to control or prevent outbreaks of pathogenic microbiota or parasites. Disinfection treatments include UV irradiation and ozone dosage. Both are generally applied to a side loop in the RAS; part of the recirculating water flow is treated. To be most effective these treatments should be applied to water with low levels of solids and dissolved organic compounds. Therefore they are generally applied as one of the last steps before the water is returned to the fish. Ozone oxidizes organic matter. It therefore not only functions as disinfectant but is also applied to breakdown dissolved organic compounds.

Ozonation and protein skimming

Ozone can be applied to reduce numbers of pathogens and parasites as well as the removal of dissolved organic compounds. Ozone is a strong oxidant that is added to the water in a side loop of the water treatment facility in a RAS. Often ozone application is combined with protein skimming. In these cases the ozone is dosed in a protein skimmer where is not only oxidizes organic matter but also produces foam. Fine solids (small particles) that were too small to be removed by mechanical filtration, are caught in the foam and removed from the system water with the foam.

Temperature control

The water a RAS may need to be heated or cooled to maintain the species specific optimal temperature for growth. Thermostatic control is applied to keep the temperature stable. Large part of the heat is in fact produced by the fish stock itself. RAS are generally placed in well insulated buildings to prevent excessive heat losses and consequently high costs for temperature control.

Ventilation

Ventilation of the air in the building in which the RAS is placed is required to remove excess carbon dioxide and humidity. In case trickling filters are used for nitrification, these are generally actively ventilated to promote is double functioning as carbon dioxide stripper. Ventilation may have a strong effect on the heat-balance of the RAS.

Oxygenation of the water

Oxygenation of the water is needed to ensure the transport of sufficient oxygen to the fish. Aeration is insufficient as the maximum oxygen concentration then reaches equals 100% saturation. Oxygenation by added pure oxygen to the water results in super saturation (>100%) and thus high levels of dissolved oxygen. Oxygen is added to the water with an oxygen reactor for which various different systems exist. The main principle is that pure oxygen is dissolved in water under high pressure to reach super saturation.

Water replacement

Part of the water in a RAS is replaced continuously or in batches. The amount of replacement water typically varies from 1 to 20% of the total system volume per day, depending on the types water treatments in the system, the fish biomass, the feed load to the system and the water quality requirements of the fish. Water replacement aims to top off the accumulation of compounds that are produced but not (sufficiently) removed in the system. Harvest operations, evaporation and removal of solids from the systems also results in water losses that need to be replaced. Although RAS require only a fraction of the water required by flow through systems, the local possibility to take in water in of sufficient quality and in sufficient amounts as well as the possibility to discharge water remain essential for the realization of RAS. RAS effluents are discharged to open water or sewer systems, with or without end of pipe treatments, all depending on local situations and regulations.

Treatment of RAS intake water

Depending on the quality of the intake water and the water quality requirements for the RAS operation the intake water may need to be pre-treated before entering. Pre-treatment may include mechanical filtration to remove solids and disinfection to remove pathogens or parasites.

Treatment of RAS effluents

Treatment of RAS effluents refers to any treatment between the recirculation loops and the point of discharge. These treatments can be aimed at disinfection, removing dissolved wastes such as phosphates and nitrates and (or) removing (organic) solid wastes. RAS effluent treatments are often installed to comply with local regulations for waste water discharges and hygiene or the reduction of costs for pollution fees.

Advantages and disadvantages compared to other systems

The most important advantages of RAS compared to open systems such as flow through tanks and cage systems are a minimum water demand, limited space demand, reduced water and nutrient discharges, stable and controlled water temperature to optimize productivity, stable and controlled water quality, tight control of feeding to maximize feed conversion efficiency, rather site independent, exclusion of predators and climatic events, low use of chemicals, constant quality of the end product and year-round production. Balanced against these advantages, RAS typically require high capital costs to set up, are technically complex, and technical failures can result in rapid, serious crop losses. RAS place greater demands on management control, feed design, health management, and demand professionalism in their use and therefore should run as optimal as possible to ensure economic viability.

Limited water availability

RAS require far less water than open aquaculture production systems such as flow through, cage and pond systems. This low water requirement of RAS allows for aquaculture production on sites where the quantity of the available water is insufficient for aquaculture production in open systems. In cases where water quality is insufficient, the low water demand of RAS may also allow for water treatment prior to its use for aquaculture. Limited water availability may be due to natural conditions or legal restrictions related to water use for aquaculture.

Reduced nutrient and water discharge – reduced environmental impact

RAS limit and provide control over nutrient and water discharge resulting from aquaculture. This may allow for aquaculture production on sites where water and nutrient discharge is (legally) restricted. In addition the control over nutrient flows allows for controlled and responsible discharge and reuse of nutrients from aquaculture, reducing its environmental impact.

Temperature control

All aquatic species have clear, species specific temperature optima for growth. Water temperatures below and above these optima result in lower growth rates and underutilization of production potential. Due to the low system water renewal of RAS a large part of the energy invested in either heating or cooling of the water in the system is retained in the system instead of being discharged with the farm's effluent. This retention of energy allows for cost effective temperature control. Temperature control allows for the installation of optimal growth temperatures year-round and independent from conditions outdoors.

Year-round production

As for the above mentioned temperature control, RAS can provide optimal conditions for aquaculture production year-round and independent from conditions outdoors. This allows for season independent production planning and market supply, which in many cases offers significant competitive advantages.

Biosecurity

Open aquaculture productions systems are exposed to pathogens and toxic compounds that can be transmitted via the water source used to supply the system with water. In RAS this exposure is reduced as for the much lower intake of water. In addition, the low water demand of RAS may allow for the use of safe but limited water sources such as wells or even tap water. The low water demand of RAS also allows for effective water disinfection treatments prior to its use in the farm, e.g. by sand filtration, UV or ozone. As for the relative compactness of RAS, it is often feasible (if not necessary) to place RAS indoors. This effectively isolates the system from outdoor influences and allows for more elaborate hygiene measures. In addition, it allows for effective measures to isolate pathogens and fish within the farm and prevent spreading of diseases via the farm effluent. Altogether, RAS offers the opportunity to significantly enhance biosecurity. This is especially important for brood stock, hatchery and nursery facilities.

Compact production system

To be economically feasible, production in RAS needs to be intensive. As a result RAS are often more compact, i.e. require less area to realize the same production as flow through systems. On sites where land is scarce or expensive this may provide an important competitive advantage.

Feasibility

RAS cannot always provide an economically viable alternative to flow-through and cage systems. In areas that offer access to water of sufficient quality and insufficient quantity, while discharge of water and nutrients from the farm is not restricted, there may be no incentive for RAS application. Under these conditions cost of production in RAS will most likely be higher compared to production of the same fish species in flow through and cage systems. Consequently RAS only provide an economically viable alternative to flow-through and cage systems in case of restricted access to water, (legal) limitations regarding nutrient discharges, geographical conditions or climatological conditions limiting the use of flow through or cages systems, or in specific cases in which RAS offer significant technical and therefore competitive advantages such as temperature control and increased bio-security.

History, state of the art and current use

RAS technology has evolved significantly in Europe over the last several decades, thanks to both publicly funded research and development programmes and private investments. As a result, the technology is currently successfully used for the commercial production of several freshwater fish species, such as European eel, pike-perch, rainbow trout and African catfish in The Netherlands and Denmark. The application of RAS technology for marine fish production is increasingly prevalent during the hatchery and nursery phases of seabass and seabream in the Mediterranean region, while commercial production of turbot in RAS is now being applied in France, Germany, the UK, Denmark and The Netherlands. The most recent development which is expected to accelerate further development of RAS technology is the gradual adoption of RAS by the salmon industry. The salmon industry initially used RAS to replace land-based flow through systems for the production of the freshwater stages of salmon. This development was mainly driven by the need to reduce fresh water demand due to increasingly limited availability or new legislations related to water use. The next step is RAS to replace sea cages for the grow-out of salmon to market size.

In conclusion, the decision to apply RAS to farm fish requires a detailed and site specific analysis of the advantages and disadvantages of RAS compared to alternative and competing production systems.

2.3 Culturing of seaweeds and mussels

2.3.1 Recirculating Aquaculture System (RAS) versus Suspension Culture System (SCS)

Seaweed and mussels can be cultivated in open systems such as suspension culture systems (SCS) or recirculation aquaculture system (RAS) that consist of tanks in which the aquatic organisms are housed combined with water treatment facilities. Similar to the application for fish, RAS are typically land-based and indoors. RAS has already been described for fish (see above for details) but can also be applied for seaweed and shellfish cultivation. Although the same main processes apply, the means of production for seaweed (nutrients) and mussels (phytoplankton, total particulate matter (TPM)) differ as well as the treatment of discharge water. A disadvantage of RAS is that it is mechanically sophisticated and biologically complex. Although this technique is preferred for fish farming a major difference between fish aquaculture versus mussel or seaweed farming is that the latter two can be produced in non-feed based open systems, whereas fish farming always requires additional feed and in addition has a much higher impact (high nutrient loading, diseases) on the environment. In open systems such as suspension culture systems (SCS) the production of seaweed and mussels depends on the available nutrients (seaweed) and feed for mussels (phytoplankton, TPM). Other environmental parameters such as temperature, visibility (Light attenuation), oxygen and pH are also uncontrolled in open systems. The open exchange of the uptake (seaweed) and excretion (mussels) of nutrients (ammonium, phosphate) can lead to nutrient depletion or nutrient loading of the direct environment. These impacts depend on the production scale and ecosystem. However these disadvantages do not way up against the high capital costs and technical complexity of RAS and therefore SCS are generally the preferred method in seaweed and mussel aquaculture.

2.3.2 Open culture systems: seaweed and mussels

Mussels can be cultivated by using bottom-culture techniques or suspended culture techniques on floating long lines also referred to as off-bottom culture. Disadvantages of using bottom-culture are that the mussels suffer higher predation from eider ducks, star fish and crabs (Capelle, 2018). In addition this technique depends on mussel seed from the wild. The stock of these seed mussels can vary each year, making yield unpredictable. Moreover the multi-use of wind parks does not allow for trawling of the sea bottom, due to damage to wind park infrastructure (cables). For the purpose of mussel cultivation in the North Sea in combination with wind parks it is therefore suggested to focus on suspended culture techniques. Both mussels and seaweed can be cultivated on long-line systems. Conditions for longline cultivation of mussels have been described in Kamermans et al (2016) and include i. Adequate robustness of the system to withstand weather conditions, usage and passage ii. Sufficiently balanced buoyancy iii. Preventing loss of mussels that fall of the ropes and iiii. Reliable and robust harvest techniques (Kamermans et al., 2016). Submerged long lines appear most suitable in environments with high seas (Langan & Horton, 2003). In a submerged system the main horizontal line is deployed at a depth of at least 10m. In this way the waves travel above the main line.

There are different constructions possible for the cultivation of seaweed and mussels. Seaweed cultivation methods can be divided into the following four systems: long line, mat systems, net systems and ring systems. Mussel farming techniques can be divided in: long line systems, cages, rafts and poles. Here we provide an overview of the construction mechanisms of these systems and their main advantages and disadvantages.

1. Long line system

Long line systems are extensively used in mussel aquaculture. This is a relatively simple structure that is kept in place with anchors and buoys (Fig. 1). The seaweed or mussels are grown on vertical lines suspended from the rope structure, or one rope that is oriented in a 'V'-shape (Fig.1). Alternatively, seaweeds or mussels can grow on the main horizontal long line. These long lines can be semi-submerged, submerged or buoyant depending on the farming environment. This technique is largely used in New Zeeland, Ireland and Chile. The long line system is used on an offshore pilot location of the *Noordzeeboerderij*. Long lines can be orientated parallel (Fig. 2) or perpendicular to the main current direction. Parallel orientation of long lines results in higher friction than perpendicular orientation and, however this difference is small, could lead to a higher reduction of current flow (Rosland et al., 2011).

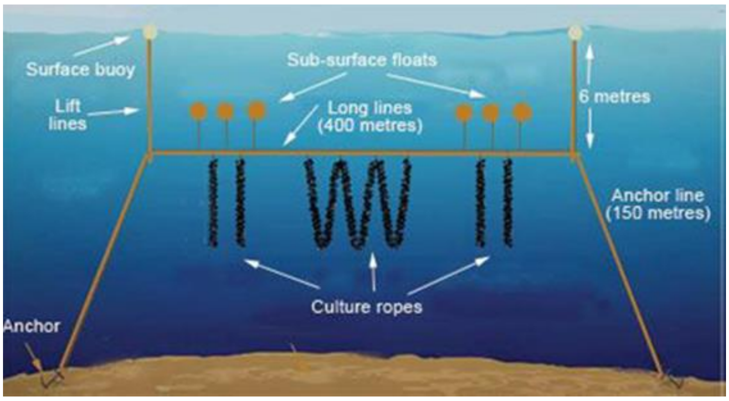

Figure 1 – Long line system (MESA, 2018)

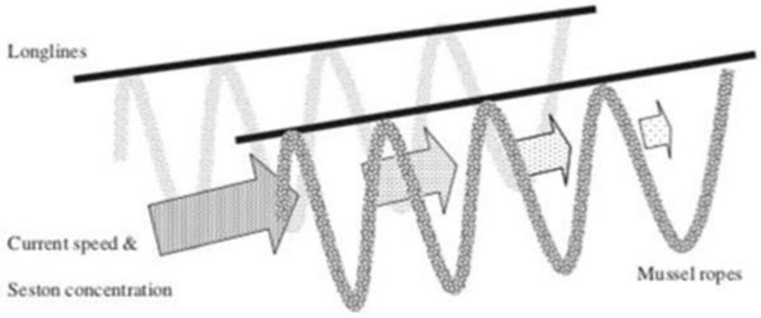

Figure 2 – Parallel oriented long lines with mussel ropes (Rosland et al., 2011)

The parallel orientation could lead to a nutrient deficiency for the seaweeds at the end of the line. The mussel yield decreases further downstream on the rope, because the nutrients are already taken up by the mussels upstream. In this way the amount of nutrients could be depleted at the end of the long lines. The shorter the long lines, the higher the mussel yield but the lower the wave reduction capacity. A perpendicular orientation gives a higher certainty that enough nutrients are available for all seaweeds on the rope, because the seaweeds all face approximately the same flow current. A disadvantage of the long line system is the difficulties of getting the construction in place and with the right amount of tension in the ropes, especially when cultivating at sea with strong waves and currents. However, this method is used worldwide for of both seaweed and mussel cultivation (Liu et al., 2004, Rosland et al., 2011).

A long line system consists of several long lines arranged in a grid (Fig. 3). The separate long lines are connected to each other with ropes. The spacing between the individual long lines cause differences in the ability to reduce the flow. The closer the distance between long lines, the higher the flow reduction capacity of the mussels (Rosland et al., 2011). However, with that also the mussel yield decreases faster when moving downstream. The spacing of cultivation ropes is similarly important in seaweed culture. When cultivation ropes would be placed above one another light reaching to deeper macroalgae could become limited, potentially reducing growth. This problem might be mitigated through a diagonal orientation across the water column, such as a stair structure. However, this design will likely counteract harvest efficiency.

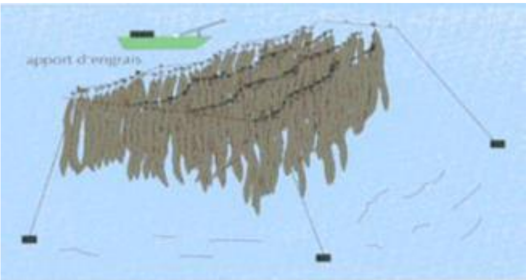

Figure 3 – Long line 3D. (Reith et al., 2005)

2. Nets

A net (Fig. 4) is suspended vertically in the water column. The thickness of the ropes and the mesh size vary for the morphology of the seaweed species, such as size and rigidness, as well as for the water motion and sediment composition of the environment. Nets can be used in intertidal or subtidal zones, depending on the species that will be cultivated (Titlyanov & Titlyanova, 2010). The expectation is that nets have a stronger effect on reducing the flow velocity, since it covers a bigger part of the water column then, for example, long lines. When connected to the Space@Sea floater this will have an impact on the (mooring) forces and will have a damping effect for the floater motions. As a result of a flow reduction, sedimentation will probably also be enhanced. When connected to the

Space@Sea floater this will have an impact on the (mooring) forces and will have a damping effect for the floater motions.

Figure 4 – Net system with seaweed (Hortimare, 2018)

3. Textile mats

The use of textile seaweed mats, instead of ropes or nets in a grid system is a recent innovation (Fig. 5). These substrate mats are suspended in a construction of textile based buoys and ropes parallel to the water surface at a depth between one and three meters. The use of textile offers many possibilities, because it is relatively cheap, strong and flexible and therefore suitable to use at sea. The AT~SEA initiative, which is funded with subsidies from the EU, is a collaboration between textile companies, seaweed producers and research institutes, including ECN to develop textile mats as a seaweed cultivation method (AT~SEA, 2018, ECN, 2018). Since this method is still in development, not much is known about the durability of these structures or their ability to survive high hydraulic loads (i.e. rough weather conditions).

The expectation is that these mats will cause a high friction, both because they are placed parallel to the main current and because they are closed mats, thus creating a higher surface area on which friction would occur than for example a grid system of ropes.

Figure 5 – Left: Mat system with seaweed being harvested. Right: mat system placed in the sea. (ECN, 2018)

4. Ring system

A ring system consists of a circular frame with carrier ropes, held into place by an anchor and a buoy (Fig. 6). The seaweed is cultivated on culture lines stretched circularly on the frame. This construction floats at a depth of 1.2 to 1.5 m (Buck & Buchholz, 2004).

A major advantage of a ring system is the ease of handling and harvesting of the seaweed. The construction can be lifted out of the sea by (boat-based) cranes and brought to shore. Ring systems are very firm, so could easily survive rough weather conditions: 2 m s^{-1} current velocities and 6 m high waves (Buck & Buchholz, 2004). However, ring systems are relatively small (± 5m diameter) and cannot easily be scaled up, because then they will lose their strength and advantageous harvesting method They normally have a diameter of 5 m. Experiments by Buck & Buchholz (2004) yielded a fresh weight of 300 kg of *S. latissima* on the ring. This is relatively low compared to the yield of a rope system. In France, the general yield of a rope system is 20 kg m^{-1} (Taelman et al., 2015)). Also, the ring construction can only be applied at water depths more than 5 to 8 m (Buck & Buchholz, 2004).

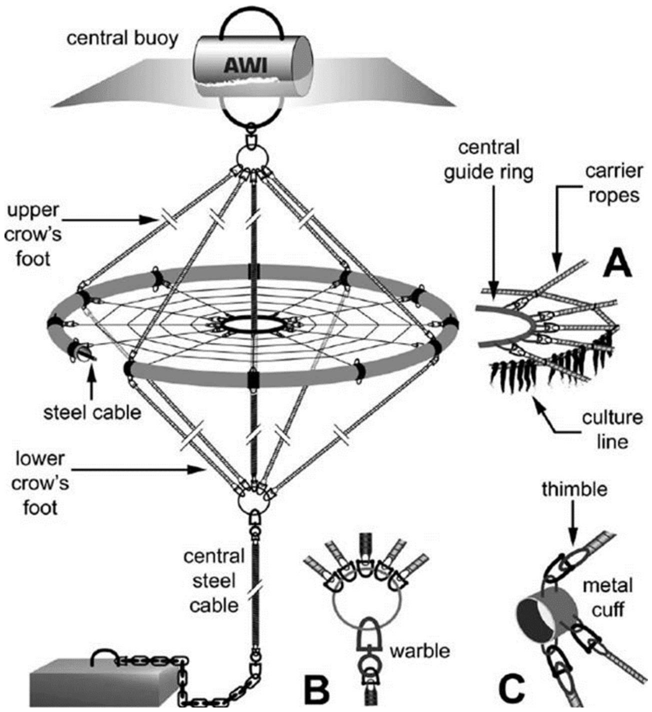

Figure 6 – Ring system (Buck & Buchholz, 2004)

5. Cages attached to poles

A new system designed for offshore mussel cultivation is the combination of cages suspended from poles (Kamermans et al., 2016). Cages are used instead of ropes, that wear easily and rely on more regular maintenance. A potential advantage of this system is the higher catchment of mussel seed per m2 compared to long line system (Kamermans et al., 2016).

6. Mussel rafts

Mussel raft consist of mean beams, cross beams and hanging beams. Mussel ropes are suspended from the raft. The mussel raft used in Spain is also known as “bateas”, these rafts are composed of a solid structure from which the mussels hang in the water. This technique is predominantly used in Spain.

Submerged longlines seem the most suitable for conditions with high waves (Kamermans et al., 2016). With a submerged system, the horizontal main line is at least 10 meters depth. The waves then cross the main line. To keep enough space underneath for the mussel ropes and play in connection with tidal heights, the location should be deeper than 20 meters. Kamermans et al. (2011) advise on the basis of an inventory of existing offshore mussel cultivation systems that the most suitable systems for the shallower North Sea are semi-submerged longlines anchored with concrete blocks. These systems are used in the French Mediterranean Sea (Mille & Blachier, 2009), and are knwon to be used along the English south coast, the Portuguese coast, the east coast of the United States (Lindell et al., 2011), in the Black Sea in Turkey (Karayucel et al., 2015) and in New Zealand (Cheney et al., 2010). The depth of immersion depends on the wave height and the depth of the longlines depends on the total water depth. Such a system has not yet been tested on the North Sea, so it is not known whether it is robust enough for the circumstances out there.

2.3.3 Environmental suitability

All the design options are suitable to the offshore environment of the North Sea. However, each cultivation method comes with advantages and disadvantages in this environment. Long line structures are widely used and strong enough to handle the currents and waves on the North Sea. However, a study by Buck & Buchholz (2004) concludes that long lines can become relatively labour intensive, because of the required maintenance and fixing of the long lines. Nets and mats are quite tight and rigid structures, especially textile mats. It is therefore expected that these nets and mats are more vulnerable to the high loading that they experience. Lastly, ring systems are specially designed for the rough conditions experienced offshore and require relatively little maintenance, however their small-scale and the complications with upscaling make them unsuitable for large scale seaweed cultivation and are therefore unlikely to be cost-efficient.

2.3.4 Harvesting methods

Seaweed can either be harvested manually using hand held tools or mechanically using machinery. Examples for machinery are; seaweed trawl, paddle wheel cutter or vacuum sucker. Mussels are generally harvested using traditional harvesting methods. These are often based on the extraction of long lines, followed by semi-automated stripping of the lines. Brushes, water flow and metal strips are used to detach the mussels from the rope. Economic feasibility of these systems is under pressure.

Automation of labour intensive process-stages is currently developed and explored. Equipment using venturi-technology is developed and applied for different production systems.

For the harvesting of mussels, different technologies are being developed and applied, which separate the mussels from the ropes under water, followed by pumping and blowing systems to remove and transport the product.

In bays with deep waters and bays with rocky shores, rafts and longlines are more commonly used for the grow-out of mussels, while seed for off-bottom culture is obtained mainly with seed collectors. In case natural settlement is scarce, seeds need to be collected otherwise, e.g. from seaweeds (Jeffs et al. 1999). However, the origin of the seed is important for further grow-out. Innovations in grow out techniques for long line and raft culture are mainly directed towards the investigation of optimal stocking densities and farm configuration (Kamermans & Capelle, 2019). To improve the performance of raft cultures under harsh offshore conditions, innovations are being made to use submerged raft designs (Wang et al., 2015) and to adapt the raft design and its orientation to optimize food availability (Newell & Richardson, 2014). Additional improvements are needed to control biofouling on mussels and on culture ropes or nets in order to improve the growth and quality of mussels (Sievers et al., 2013). The best way is to reduce the settlement of natural fouling organisms. This could be achieved by ensuring 100% occupation of the ropes by mussels, or by manual removal of fouling, or by using antifoulants (Fitridge et al. 2012).

2.3.5 Wave reduction and sedimentation enhancement of seaweed/mussel cultivation

Each of the cultivation systems will have different effects on waves, currents and sedimentation. Parameters that need to be taken into account when maximising drag, and thereby reducing waves and currents, are raft orientation to current direction, raft size, raft aspect ratio, and rope spacing (Newell & Richardson, 2014). Reduced waves and currents can in turn lead to enhanced sedimentation.

2.4 Development of a microalgae cultivation system

Irrespective of different arrangements for the basic design for the outlined aquaculture applications in section 3.2, e.g. on, between and next to the platform, respectively, a microalgae cultivation system has to be developed for offshore use and, therefore, needs to deal with challenges and synergies which are available offshore.

In order to ensure a stable mass production of microalgae at any place, an efficient and continuously working supply of inoculate culture is crucial. In doing so, a closed system – a so-called photobioreactor – should be arranged on the platform in such a way that stable growth conditions can be ensured. Also, synergy effects, e.g. the heat capacity of the seawater and the seawater itself as culture media, should be used in order to create an efficient cultivation process.

A double-wall tubing system (figure 1), which has been developed and already successfully tested for onshore usage, therefore, could be used for the development of an offshore application. Providing the cultivation chamber for the microalgae culture on the one hand, the second chamber is supposed to be used for temperature control, and in the case of an offshore application, the water could be directly taken from the sea as well as given back to the ocean after going through the cooling cycle – the system is completely integrated and closed, so that there is no contact to the microalgae culture (figure 2 - left). The material is based on silicone, so that it is suitable to be used with seawater. Also, the durability against harsh UV radiation has been tested in earlier experiments.

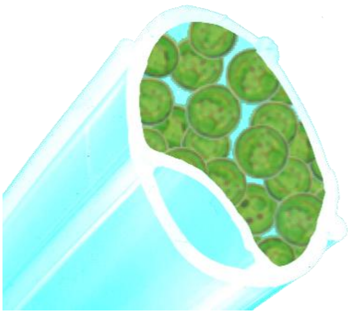

Figure 7 – flexible and transparent double wall tubing system based on silicone, being filled with microalgae culture (depicted green cells) and second chamber for filling with air/CO_2 and water for depth leveling and possible CO_2 supply

The basic design of the photobioreactors using the double wall tube for offshore application is based on the onshore photobioreactor system and, here, has to be adapted to offshore conditions and the needs on a more or less, independently working environment at sea. To create high surface to volume ratios on a given ground area, the conical shaped light collectors, consisting of the double wall tube, offers an efficient way to collect the sunlight during the entire day. Especially at offshore conditions, providing high rates of radiated surfaces at any time and sun elevation is of great importance, as there is the maximum value of sunlight hours compared to land areas (no shading effects as a consequence of geographic parameters). By means of the conical shape design, high levels of capturing sunlight offer the potential of high biomass productivities under offshore conditions. Figure 2 (right) shows an approach of the arrangement of light collectors in a manner of 8 collectors being individually connected to one mixing tank. In that way, a scalable system by numbering up several modules can be arranged on a triangular shape. With this, a secure and stable production of inoculate biomass of microalgae is ensured.

Furthermore, the flexible tubing system offers the direct use in seawater. In that way, the heat capacity and the wave energy can be directly and consistently used to control the microalgae temperature and mixing of the culture. Therefore, a floating device has to be developed in order to arrange an appropriate size of cultivation volume. As mentioned in figure 1, the second chamber of the tubing system can be used to control the water depth by a defined volume of water and air. In this way, high wave loads and, thus, a possible risk to the tubing system can be avoided by lowering the water depth. Another benefit of controlling the water level is the possibility to prevent the algal cells, if necessary, from high sun radiation.

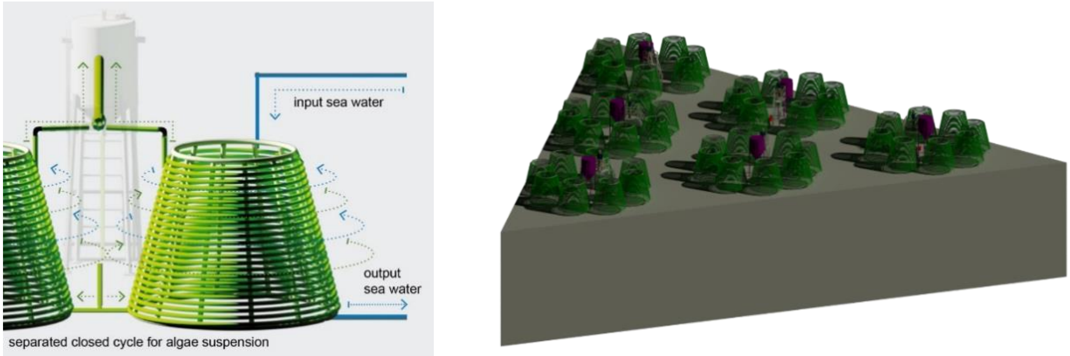

Figure 8- left: light collector and use of double wall tubing system – use of seawater in counter direction of flow of microalgae culture

right: 3D view of triangular shaped single module for inoculation production of microalgae (6 x 8 conical shaped algae reactors)

Figure 3 shows a principle design concept of a small floating island structure of a microalgae production site. It depicts several triangular modules connected to each other and serving as O&M hub (this figure is for explanatory purpose only, the Space@Sea floater will be rectangular). In doing so, next to the microalgae production for inoculum on the platform (see figure 2), there are designated areas for facilities for maintenance and logistics, processing of the biomass and storage of the feed and product, as well as general working and living environment for workers. The floating modules for microalgae production are depicted left and right of the island, respectively.

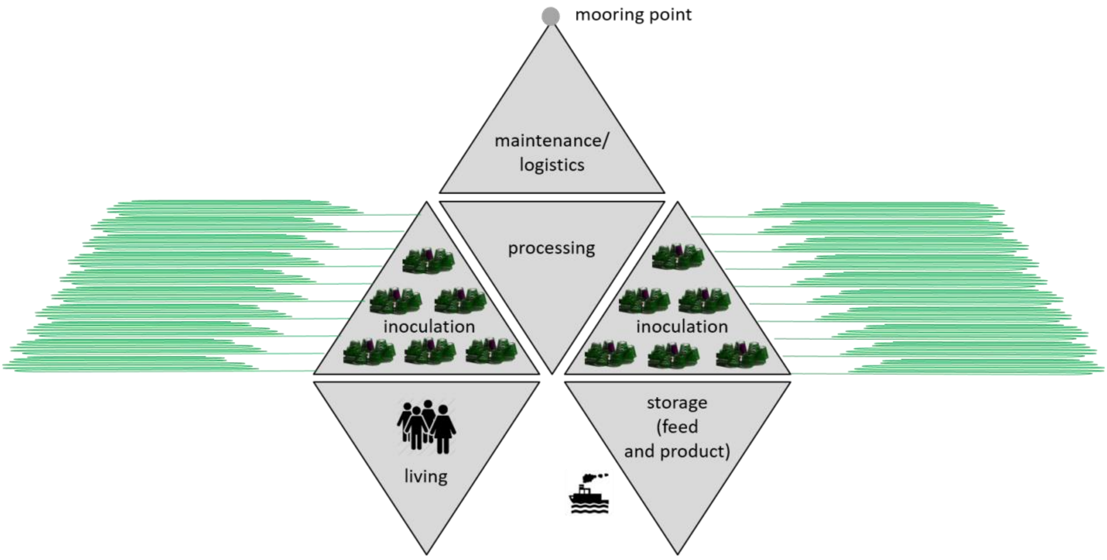

Figure 9 - Design concept of small floating island of microalgae production site

As practical approach, the overall suitability of production can be calculated. Assuming a cultivation volume on the platform of 28.8 m³ (volume of light collector approximately 300 l, neglecting peripheral volume) gives a required size of production volume for the floating modules of 288 m³, assuming a commonly used factor of 10 for upscaling. Applying an average daily biomass productivity of 0.2 g l^{-1} d^{-1} (low assessment) the total daily overall production of microalgae biomass would be 57.6 kg based on dry weight. Considering a quite small 100 t salmon aquaculture farm (60 m circumference – 15 m depth fish net, or a tank based system), this amount could be sufficient to substitute the regular feed by a value of several per cent (depending on the fish in-fish out ratio), which gives a high potential to cover the demand of protein and PUFA’s.

3. Aquaculture concepts for floating modules

3.1 Methodology

In Chapter 2 possible aquaculture systems for the culturing of fish, mussels (bivalves), seaweeds and microalgae are introduced and described. In the current chapter, an evaluation will be made on the possibilities for culturing these organisms in systems to be applied in conjunction with floating modules. on-top of the floating modules, or in between, under, within, or adjacent to the modules, for each of the organisms as listed above. When considered relevant, a factsheet is provided in the Annex, including a system description, characteristics and requirements and a Strength, Weaknesses, Opportunities and Threats (SWOT) with regard to several, mainly technical, criteria. With a focus on fish, mussels, seaweeds and microalgae, 26 options were selected for developing factsheets.

3.2 Configuration of aquaculture systems

There are several options for deploying aquaculture systems and therefore several configurations are possible (See Table 1). These will also depend on location and species.

Options are:

1. On top of modules, depending on location, fish/microalgae/seaweed/ sea cucumber may not be held in cages and therefore culturing in system on deck may be an option. Economic considerations will probably determine the scale (dimensions) that are required.

2. Some aquaculture systems could in principle be deployed under the floating modules. Since seaweeds and microalgae require (sun)light for their growth, this option is not suitable. However, the culturing of fish and mussels should be possible in case technical requirements could be met.

3. In between the modules. Open spaces within the island may serve as culturing locations. These may be suitable for culturing fish and shellfish (mussels). For seaweed and microalgae, shadowing by the floating modules may create less favorable conditions with regard to light availability is deployed in the water column (in between modules). Other possible species in between the modules could be Sea Urchin and Scallops (farmed in basket systems), who not required light for growth.

4. “Open modules” may be created that may be more “rigid” than option 2 (where modules may act as moving parts). The modules may be open so including a water surface, or closed with a bottom. The benefits as compared to the options on-top and in between needs to be evaluated. Modified modules may further oppose to the principle of developing standardized modules.

5. Culture systems could be secured to a module on the outside border of the floating island, or could be anchored independently. In the latter case, the floating island may serve as working deck, but the culture system itself could be independent from the floating module(s) structure.

Table 1 Potential combination of culturing of groups of organisms in different modes of culture in relation to the use of floating modules (substructures) of an offshore island

Mode of culture	Fish	Shellfish	Seaweed	Microalgae
Recirculation Aquaculture Supersystem (on top)	X*	X	X	X
Production under substructures	X	X	-	-
Production inside adapted subsystem	X	X	X	X
Production between substructures	X#	X	X	X
Production connected to subsystem	X#	X	X	X
Production in proximity of subsystem	X#	X	X	X

* also flow through system is considered

also cage systems considered

3.3 Factsheets

For each relevant combination as provided in Table 1 a factsheet is provided as presented in Annex 1.

Situation	System	Organism	Factsheet	Page
On top	RAS	Fish	1	27
	Flow through	Fish	2	29
	RAS	Shellfish	3	31
	RAS	Seaweed	4	32
	RAS	Microalgae	5	33
Under	CCAS	Fish	6	34
	SCS	Shellfish	7	35
Inside	CCAS	Fish	8	36
	SCS	Shellfish	9	37
	SCS	Seaweed	10	38
	CCAS	Microalgae	11	39
Between	CCAS	Fish	12	40
	Cage	Fish	13	41
	SCS	Shellfish	14	42
	SCS	Seaweed	15	43
	CCAS	Microalgae	16	44
Connected outside	CCAS	Fish	17	45
	Cage	Fish	18	46
	SCS	Shellfish	19	47
	SCS	Seaweed	20	48
	Closed floating system	Microalgae	21	49
In proximity	CCAS	Fish	22	50
	Cage	Fish	23	51
	SCS	Shellfish	24	52
	SCS	Seaweed	25	53
	CCAS	Microalgae	26	54

4. Discussion and conclusions

This report provides an inventory of aquaculture options for fish, shellfish (mussels), seaweeds and microalgae to applied in conjunction with floating modules. Factsheets are provided in order to describe and compare relevant aspects to enable a further selection of the most promising aquaculture options. These will also depend on the location where systems will be deployed and on combinations with other functions imagined for the floating islands. It is also possible to combine different types of aquaculture, which may have additional benefits, as elaborated in concepts for Integrated Multi-Trophic Aquaculture systems (IMTA). In here, the culturing of several trophic levels are combined in such a way that synergistic effects may stimulate production and reduce the ecological footprint. Basically, IMTA systems combine fish cages where food is added to stimulate the growth of fish, with shellfish filtering the water from organic waste particles (surplus of feed and excreted particles), and seaweeds taking up dissolved nutrients from waste streams. The effective functioning of IMTA systems depends on various aspects, including the location and area specific conditions, such as depth and water current, the type of culture systems and there dimensions, the species to be cultured and the spatial configuration (in-between distance). A generic description is therefore nor provided here.

Based on this inventory and descriptions of systems, a selection will be made for further elaboration. We propose a multi-criteria analyses by making use of expert judgement, to select the most promising options. These will form the basis for the description of optimal design options to be elaborated in Task 8.4 (Definition of optimal design options for selected aquaculture activities) and Task 1.4 for developing business cases of WP 1 of the Space@Sea project.

For the multi-criteria analysis, criteria need to be developed that enable an assessment of the technical feasibility, the economic viability and environmental suitability. For each aquaculture industry the various design options will be assessed by such a multi-criteria analysis to identify which of the six design options (on top, under, inside, in between, connected to the outside and in proximity of) have the highest potential per case study (fish, shellfish, seaweed and micro-algae). The criteria can be weighted based on the importance of the criteria in the specific case study. Subsequently the criteria will be rated on the performance of each design option. These criteria will be developed in order to select aquaculture options for which an optimal design will be defined, being part of Task 8.4 and reported in Deliverable 8.3 of the Space@Sea project (Optimal design options for aquaculture at modular floating islands).

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Annex 1: Factsheets for aquaculture options

Factsheet	Title
1	Factsheet Recirculating Aquaculture System (RAS): Fish culture on top of substructure
2	Factsheet Flow through tank system: Fish culture on top of substructure
3	Factsheet Recirculating Aquaculture System (RAS): Shellfish (mussels) on top of substructure
4	Factsheet Recirculating Aquaculture System (RAS): Seaweed - on top of substructure
5	Factsheet Recirculating Aquaculture System (RAS): Microalgae - on top of subsystem
6	Factsheet Cage culture or Closed Containment Aquaculture System CCAS: Fish - UNDER substructures
7	Suspension Culture System: Shellfish - UNDER substructures
8	Factsheet Cage culture or Closed Containment Aquaculture System CCAS: Fish - inside substructures
9	Factsheet Suspension Culture System: Shellfish - inside substructures
10	Factsheet Suspension Culture System: Seaweed - inside substructures
11	Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae - inside subsystem
12	Factsheet Closed Containment Aquaculture System CCAS: Fish - BETWEEN substructures
13	Factsheet Cage Aquaculture System : Fish - BETWEEN substructures
14	Factsheet Suspension Culture System: Shellfish - BETWEEN substructures
15	Factsheet Suspension Culture System: Seaweed - Between substructures
16	Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae - Between substructures
17	Factsheet Closed Containment Aquaculture System CCAS: Fish - connected OUTSIDE substructures
18	Factsheet Cage Aquaculture System : Fish - connected OUTSIDE substructures
19	Suspension Culture System: Shellfish - connected OUTSIDE substructures
20	Factsheet Suspension Culture System: Seaweed – connected to outside substructures
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1. Factsheet Recirculating Aquaculture System (RAS): Fish culture on top of substructure

Description of system

Recirculating Aquaculture System (RAS)	Tank based production system inside a building with internal water treatment, low water demand and controlled conditions.
Positioning in relation to sub-structures	On top of substructure
Main product	Fish
Proposed location	Mediterranean, but also possible elsewhere

Main requirements & Characteristics

Means of production	Seawater, Feed, Oxygen, water buffering compounds (NaOH, NaHCO3), Electrical power, juvenile fish, expert labour.
Facilities	Tanks, biological and mechanical water treatments, insulated aquaculture building and Operation & Mmaintenance aquaculture building on substructure, feed supply & storage, seawater supply, pre-treatment & storage, seawater discharge, end of pipe treatment production water (optional), solid waste (organic sludge) storage and processing, high demand power supply, pure oxygen supply & storage, processing plant (optional).
Conditions	Noise control, vibration control, sloshing control, WQ standard water quality, static surface environment.
Transport & logistics	Supply all means of production except seawater from the mainland, feed/produce storage unit (cold), crane units, aquaculture support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Not specified
Metrics substructure	Mass on top of substructure (mainly water), specifically designed substructure(s) may be an option

SWOT

Strengths	Environmental benefits: controlled waste discharge, no escapees, isolated from its direct environment. Controlled optimal production conditions independent from local climate & weather. No force on system from under water structures. Established and advancing technology. Intensive production: low space requirements per unit of fish production.
Weaknesses	Technically complex. Sensitive to technical failure. High energy demand. High investment High costs of production.
Opportunities	Access to seawater. Discharge of seawater. Use of locally produced green or blue energy. Use of locally produced raw materials as feed ingredients as part of food for fish. Mitigation of threats associated to open fish production systems. Fish production in areas unsuitable for open systems. Production of exotic fish species. Season independent, constant production. Off season supply of markets. Production of juveniles and pre-ongrown fish for stocking in nearby open systems.Local fish processing. Local oxygen production with a (cryogenic) air separation unit (ASU). Automation of production.
Threats	Distance to market.

	High dependency on supply of means of production from the mainland. Competition with land-based RAS; no clear advantages over land-based RAS except access to seawater and space Competition with lower costs open production systems. Processing and discharge of solids wastes. Sloshing of water in tanks. Image.

2. Factsheet Flow through tank system: Fish culture on top of substructure

Description of system

Flow through tank system (FTS)	Tank based production system inside a building or outdoors with seawater passing through to maintain water quality, high water demand and limited control over conditions.
Positioning in relation to sub-structures	On top of substructure
Main product	Fish
Proposed location	Mediterranean

Main requirements & Characteristics

Means of production	Seawater, Feed, Oxygen (optional), Electrical power, juvenile fish, expert labour.
Facilities	Tanks, insulated aquaculture building (optional) or roof covering (optional), and Operation &Maintenance aquaculture building on substructure, feed supply & storage, large capacity seawater supply, pre-treatment (optional), seawater discharge, end of pipe treatment production water (optional), solid waste (organic sludge) storage and processing (optional in case of end of pipe treatment), high demand power supply, pure oxygen supply & storage (optional), processing plant (optional).
Conditions	Noise control, vibration control, sloshing control, WQ standard water quality, static surface environment.
Transport & logistics	Supply all means of production except seawater from the mainland, feed/produce storage unit (cold), crane units, aquaculture support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Not specified
Metrics substructure	Mass on top of substructure (mainly water), specifically designed substructure(s) optional

SWOT

Strengths	Environmental benefits: no escapees, isolated from its direct environment. Relatively simple technology compared to RAS Relatively low investment compared to RAS Relatively low costs of production compared to RAS No force on system from under water structures. Established technology. Intensive production: low space requirements per unit of fish production.
Weaknesses	Uncontrolled discharge of dissolved wastes Limited control over production conditions, influence of local climate & weather conditions. Sensitive to power failure. High energy demand. High water demand Risk of pathogens intake with intake water
Opportunities	Access to seawater. Discharge of seawater. Use of locally produced green or blue energy. Use of locally produced raw materials as feed ingredients for fish feed. Partly mitigation of threats associated to open fish production systems. Fish production in areas unsuitable for open systems. Production of exotic fish species. End of pipe treatment to limit waste discharge Pre-treatment of intake water to limit disease risks. Production of juveniles and pre-ongrown fish for stocking in nearby open systems.Local fish processing. Local oxygen production with a (cryogenic) air separation unit (ASU). Automation of production.

	Use filtered out solid wastes, e.g. as fertilizer
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition with land-based aquaculture productions; no clear advantages over land-based aquaculture except access to seawater and space Competition with lower costs open production systems. Processing and discharge of solids wastes. Sloshing of water in tanks. Image.

3. Factsheet Recirculating Aquaculture System (RAS): Shellfish (mussels) on top of substructure

Description of system

Recirculating Aquaculture System (RAS)	Tank based production system inside a building with internal water treatment, low water demand and controlled conditions.
Positioning in relation to sub-structures	On top of substructure.
Main product	Mussels (also snails like Abalone)
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, feed, mussel seed, oxygen, power supply on platform, expert quality workforce.
Facilities	Building on substructure, Aquaculture in building, O&M aquaculture building on substructure, high energy demand, environmental seawater supply & pre-treatment, end of pipe treatment production water, seawater discharge, discharge organic sludge, storage/treatment organic sludge, air supply/pump, harvesting & seeding units, processing plant (depending on costs).
Conditions	Sloshing control, WQ standard water quality, current dependence (nutrient supply) is dependent on location, static surface environment.
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture supply vessel. Transport of produce to markets on the mainland.
State of the art	Application of current technology
Time to implementation	Short
Depth location	Not specified.
Metrics substructure	Mass above substructure.

SWOT

Strengths	Environmental benefits: controlled waste discharge, no escapees, isolated from its direct environment. Controlled optimal production conditions independent from local climate & weather. No force on system from under water structures. Established and advancing technology. Low space requirements.
Weaknesses	Technically complex. Sensitive to technical failure. High energy demand. High costs of production.
Opportunities	Access to seawater. Discharge of seawater. Use of locally produced green or blue energy. Use of locally produced raw materials as feed ingredients. Mitigation of threats associated to open shellfish production systems. Shellfish production in areas unsuitable for open systems. Potential for saltwater aquaponics. Production of exotic species (but, may not be allowed) Local mussel processing. Automation of production.
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition with land-based RAS. Processing and discharge of solids wastes. Damage from heavy seas/storms. Sloshing of water in tanks. Image.

4. Factsheet Recirculating Aquaculture System (RAS): Seaweed - on top of substructure

Description of system

Recirculating Aquaculture System (RAS)	Tank based production system inside a building with internal water treatment, low water demand and controlled conditions.
Positioning in relation to substructures	On top of substructure
Main product	Seaweed
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, power supply on platform, supply of seaweed seedlings, expert quality workforce, added nutrients
Facilities	Building on substructure, aquaculture in building, O&M aquaculture building on substructure, environmental water supply, discharge of water, end of pipe treatment production water, high energy demand, supply of energy, compressed air supply/pump, harvesting units, seeding unit, processing factory (depending on cost)
Conditions	Sloshing control, WQ standard water quality, depends on location, static surface environment.
Transport & logistics	Produce storage unit (cold), crane units, aquaculture support vessel Transport of produce to mainland.
State of the art	Application of current technology
Time to implementation	Short
Depth location	Not specified
Metrics substructure	Mass above substructure

SWOT

Strengths	Environmental benefits: fewer impacts, controlled waste discharge, isolated from its direct environment. Potential to add nutrients without impacting the environment. Controlled optimal production conditions independent from local climate & weather. No forces on system from under water structures.
Weaknesses	Technically complex. Sensitive to technical failure. High energy demand. High costs of production. Lower/or altered light levels inside tanks due to shading sides. Less space, only small scale cultivation possible. No use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures). Higher force on top subsystem due to tank volume.
Opportunities	Access to seawater. Discharge of seawater. Use of locally produced green or blue energy. Potential for salt water aquaponics.
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition with land-based RAS. Damage from heavy seas/storms. Sloshing of water in tanks. Image.

5. Factsheet Recirculating Aquaculture System (RAS): Microalgae - on top of subsystem

Description of system

Recirculating Aquaculture System (RAS)	Tank based production system inside a building with internal water treatment, low water demand and controlled conditions.
Positioning in relation to substructures	On top of substructure
Main product	Microalgae
Proposed location	North sea (off shore)

Main requirements & characteristics

Means of production	Seawater, power supply on platform, micro-algae start batch, expert quality workforce, nutrient supply.
Facilities	Building on subsystem, aquaculture building and O&M aquaculture building on substructure, environmental water supply (UV filtered?), seawater discharge, end of pipe treatment, high energy demand, compressed air supply/pump, harvest/separation units, processing factory (depends on costs).
Conditions	Sloshing control (not if in bags), water quality, static surface environment.
Transport & logistics	Transport of produce to mainland, produce storage unit (cold), crane units.
State of the art	Application of current technology
Time to implementation	Short
Depth location	Not specified
Metrics substructure	Mass above substructure.

SWOT

Strengths	Environmental benefits: fewer impacts due to closed system, controlled waste discharge, isolated from its direct environment. Potential to add nutrients without impacting the environment. Controlled optimal production conditions independent from local climate & weather. No forces on system from under water structures.
Weaknesses	Technically complex. Sensitive to technical failure. High energy demand. High costs of production. Lower/or altered light levels inside tanks due to shading sides. No use of suspended culture system to dampen wave energy & currents (i.e. lower maintenance costs substructures). High force on top subsystem due to tank volume.
Opportunities	Access to seawater. Discharge of seawater. Use of locally produced green or blue energy. Combination with other aquaculture (IMTA) or wind parks.
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition with land-based RAS. High risk of damage from storms/high seas. Sloshing of water in tanks. Image.

6. Factsheet Cage culture or Closed Containment Aquaculture System CCAS: Fish - UNDER substructures

Description of system

Cage culture or Closed Containment Aquaculture System CCAS	Net based in situ (in seawater) nets are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	UNDER substructures
Main product	Fish
Proposed location	Mediterranean (off shore)

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, harvesting & maintenance requires labour and depending on harvest method may require electricity
Facilities	O&M aquaculture building on substructure, processing plant (optional), diving activities (automated).
Conditions	Limited daylight, low or high current, environmental seawater.
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	Mass below substructure, specifically designed substructure (s)?

SWOT

Strengths	Environmental benefits.... Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. Off bottom...limited seabed disturbance (but see organic decomposition) Increase water clarity. Reduce pressure fish aquaculture. No need for extra connection points outside substructure.
Weaknesses	Environmental impacts depend on scale. Forces on system from under water structures/ropes (higher maintenance costs substructures). Only small scale cultivation possible. Less or no use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Opportunities	Use of space in the Mediterranean sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or wind parks (less applicable due to limited space, depth availability). Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition with inshore fish farms. Exposure to weather, severe storms.

* specific for positioning: in between, inside, outside, on top (RAS)

7. Suspension Culture System: Shellfish - UNDER substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) ropes are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	UNDER substructures
Main product	Mussels
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, mussel seed, harvesting & maintenance requires labour and depending on harvest method may require power supply on platform.
Facilities	O&M aquaculture building on substructure, seeding unit, harvesting units, processing plant (optional), supply of energy, diving activities (automated monitoring).
Conditions	Limited light availability, low or high current, environmental oxygen & seawater supply, unstable conditions (weather dependent).
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units, aquaculture support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future
Time to implementation	Short
Depth location	Shallow water (between 10-20m under floating structure)
Metrics substructure	Mass below substructure,

SWOT

Strengths	Environmental benefits are: increased water clarity (filtration), increased biodiversity. Due to smaller scale less chance of overriding carrying capacity/ organic decomposition. Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. Off bottom...limited seabed disturbance (but see organic decomposition) Reduce pressure mussel aquaculture Wadden Sea. No need for extra connection points outside substructure.
Weaknesses	Forces on system from under water structures/ropes (higher maintenance costs substructures). Only relatively small scale cultivation possible Less or no use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or possibly wind parks (limited space available. Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition with inshore mussel farms. Exposure to weather, severe storms.

8. Factsheet Cage culture or Closed Containment Aquaculture System CCAS: Fish - inside substructures

Description of system

Closed Containment Aquaculture System CCAS	Large partly submerged, floating enclosures in situ (in seawater). Enclosures are connected to the walls of the adapted (specially designed) substructure, controlled water flow in and out of the enclosures . Treatment of intake and discharge water.
Positioning in relation to substructures	Inside substructures
Main product	Fish
Proposed location	Mediterranean and Northern North Sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power.
Facilities	Enclosures, moorings to sea floor, pre-treatment of intake water, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	Low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Recently established technology. Various variants by different companies. The technology is expected to advance further in the near future
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	Determined by the design of the adapted substructure.

SWOT

Strengths	Low energy demand compared to RAS and FTS. Treatment of intake water; low risk of pathogen intake Advancing technology. No escapes No need for extra connection points outside substructure.
Weaknesses	Recent technology, may not be fully established. Environmental claims not yet fully documented Technically more complex than traditional sea cages Environmental impacts from fish waste Forces on system from under water structures/ropes (higher maintenance costs substructures).
Opportunities	Sheltered location inside substructures Controlled discharge of solid wastes Operation from substructure; no need for large vessels (feed barge, well boats). Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

9. Factsheet Suspension Culture System: Shellfish - inside substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) ropes are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	Inside substructures
Main product	Mussels
Proposed location	North sea (offshore)

Main requirements & characteristics

Means of production	Seawater, mussel seed, harvesting & maintenance requires labour and depending on harvest method may require electricity
Facilities	O&M aquaculture building on separate substructure, harvesting units, processing plant (optional), energy supply low, diving activities (automated)
Conditions	Good light availability, low or high current (depends on nutrients availability), environmental oxygen & seawater, unstable conditions (weather dependent), no shelter/wave protection.
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units, aquaculture in support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future
Time to implementation	Short
Depth location	Shallow water (10-20m)
Metrics substructure	Mass below substructure, specifically designed substructure.

SWOT

Strengths	Environmental benefits are: increased water clarity (filtration), increased biodiversity. Due to smaller scale less chance of overriding carrying capacity/ organic decomposition. Technically simple, not sensitive to technical failure. Relatively low maintenance, low energy demand, low cost on production. Established and advancing technology. Off bottom.imited seabed disturbance (but see organic decomposition) Increase water clarity. Reduce pressure mussel aquaculture Wadden Sea. No need for extra connection points outside substructure.
Weaknesses	Environmental impacts depend on scale and will be relatively small. Forces on system from under water structures/ropes (higher maintenance costs substructures). Less space for suspension systems inside substructures, only small scale cultivation possible. Less or no use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or wind parks. Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition with inshore mussel farms. Exposure to weather, severe storms.

10. Factsheet Suspension Culture System: Seaweed - inside substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) but ropes are connected to substructures, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	Inside substructures
Main product	Seaweed
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, seedlings, harvesting & maintenance requires labour and depending on harvest method may require electricity.
Facilities	O&M aquaculture building on separate substructure, harvesting units, processing plant (optional), energy supply low, environmental seawater & CO2 supply, diving activities (automated).
Conditions	Reasonable to good light availability, low or high current (depending on nutrient availability), unstable conditions (weather dependent), no shelter/wave protection.
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Shallow water (between 10 - 20m).
Measurement substructure	Mass below substructure, specifically designed substructure.

SWOT

Strengths	Environmental benefits: sustainable, no need for nutrient input or waste management (but see factsheet 15 & 18 for decomposition seaweed fragments on bottom depending on scale). Technically simple, not sensitive to technical failure. Relatively low maintenance, low energy demand, low cost on production. Established and advancing technology. No need for extra connection points/buoys & anchorage outside substructure.
Weaknesses	Environmental impacts depend on scale (high seaweed production may lead to nutrient depletion). Forces on system from under water structures/ropes (higher maintenance costs substructures). Potential lower light levels inside substructures due to shading (depends on design substructure). Less space for suspension systems inside substructures, only small scale cultivation possible. Less or no use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA) or wind parks (less applicable due to limited space availability). Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition with inshore seaweed farms. Exposure to weather, severe storms.

11. Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae - inside subsystem

Description of system

Closed Containment Aquaculture System (CCAS)	Closed containment (in double wall tubing system) in situ (in seawater), inoculation module on platform, production as floating module next to platform (fixed connection), controlled conditions.
Positioning in relation to substructures	Inside substructure
Main product	Microalgae
Proposed location	Mediterranean Sea (off shore)

Main requirements & characteristics

Means of production	Seawater, inoculation biomass on platform, production of microalgae on floating modules inside substructures, expert labour, CO2 supply, nutrients, power supply
Facilities	On the platform: O&M, processing, harvest (e.g. centrifuge), storage (e.g. freezer), cultivation system for inoculation material of microalgae Inside the substructures: floating production modules for microalgae biomass
Conditions	Ensuring of stable production because of consistent supply of inoculation material on the platform, Stable culture temperature by means of submerged conditions of tubing system, additionally, equally light distribution and dilution
Transport & logistics	Transport and storage of feed and product (microalgae biomass) between mainland and platform, operation of floating modules takes place on platform
State of the art	No comparable system available
Time to implementation	Mid-term
Depth location	About 1 to 2 m water depth required for operation of floating production modules
Metrics substructure	Specific design to ensure an appropriate connection to floating modules (power-free, impulse-free transmission)

SWOT

Strengths	Operation of floating module takes place on platform; use of mechanical forces for mixing and seawater temperature for maintaining growth temperature of microalgae suspension; low (electrical) energy input for production in floating modules; continuous production ensured due to stable input of fresh inoculum from defined platform system; low impact on environment (closed system), no expensive rack for installation needed
Weaknesses	Hard to scale up; possible shading effects because of platform and buildings on them; dependency of culture temperature on seawater temperature. More complex design of entire platform system; as well as building structure as also facilities on top of them; size of floating module depends on substructure design (only small size of floating module possible)
Opportunities	Access to seawater Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Reduction of energy demand for microalgae production (mixing, cooling).
Threats	Dependent on nutrient supply from mainland. Competition with onshore production. Biological impact on environment has to be assessed.

12. Factsheet Closed Containment Aquaculture System CCAS: Fish - BETWEEN substructures

Description of system

Closed Containment Aquaculture System CCAS	Large partly submerged, floating enclosures in situ (in seawater). Enclosures may be are connected to substructure, controlled water flow in and out of the enclosures . Treatment of intake and discharge water.
Positioning in relation to substructures	BETWEEN substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power.
Facilities	Enclosures, moorings to sea floor, pre-treatment of intake water, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Recently established technology. Various variants by different companies. The technology is expected to advance further in the near future
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Low energy demand compared to RAS and FTS. Treatment of intake water; low risk of pathogen intake Advancing technology. No escapes No need for extra connection points outside substructure.
Weaknesses	Recent technology, may not be fully established. Environmental claims not yet fully documented Technically more complex than traditional sea cages Environmental impacts from fish waste Forces on system from under water structures/ropes (higher maintenance costs substructures).
Opportunities	Sheltered location between substructures Controlled discharge of solid wastes Operation from substructure; no need for large vessels (feed barge, well boats). Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

13. Factsheet Cage Aquaculture System : Fish - BETWEEN substructures

Description of system

Closed Containment Aquaculture System CCAS	Large d, floating netpens or cages in situ (in seawater). Cages may be are connected to substructure,
Positioning in relation to substructures	BETWEEN substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power
Facilities	Cages , moorings to sea floor, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Established technology.
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand compared to RAS and FTS. Established technology.Low production costs compared to other aquaculture systems No need for extra connection points outside substructure.
Weaknesses	Environmental impacts from solid waste and escapes Limited control over water quality Substructure blocking water currents required for water exchange cages.
Opportunities	Sheltered location between substructures Mooring to substructure Operation from substructure; no need for large vessels (feed barge, well boats). Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

14. Factsheet Suspension Culture System: Shellfish - BETWEEN substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) ropes are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	BETWEEN substructures
Main product	Mussels
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, mussel seed, harvesting & maintenance requires labour and depending on harvest method may require electricity.
Facilities	O&M aquaculture building on substructure, harvesting units, processing plant (optional), energy supply low, diving activities (automated).
Conditions	low or high current (depends on nutrient concentrations and scale), environmental oxygen & seawater, unstable conditions (weather dependent), some shelter/wave protection.
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future
Time to implementation	Short
Depth location	Shallow water (between 10 – 20m).
Measurement substructure	Mass below substructure.

SWOT

Strengths	Environmental benefits: increased water clarity (filtration), increased biodiversity. Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. Off bottom...limited seabed disturbance (but see organic decomposition). Reduce pressure mussel aquaculture Wadden Sea. No need for extra connection points outside substructure. Potentially more space for suspension systems outside substructures, larger scale cultivation possible. Depending on scale the use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Weaknesses	Environmental impacts depend on scale. The larger the scale the more chance of overriding the carrying capacity or impacting the benthic community (organic decomposition). Forces on system from under water structures/ropes (higher maintenance costs substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or wind parks (less applicable due to limited space availability). Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition with inshore mussel farms. Exposure to weather, severe storms.

15. Factsheet Suspension Culture System: Seaweed - Between substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) but ropes are connected to substructures, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	In between substructures
Main product	Seaweed
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, seedlings, harvesting & maintenance requires labour and depending on harvest method may require electricity.
Facilities	O&M aquaculture building on substructure, harvesting units, processing plant (optional), energy supply low, diving activities (automated), environmental seawater & CO2 supply.
Conditions	Limited light availability (due to shading substructures/buildings), low or high current (depends on nutrient concentration and scale), unstable conditions (weather dependent), limited shelter/wave protection, WQ standards.
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future
Time to implementation	Short
Depth location	Shallow water (between 10-20m).
Metrics substructure	Mass below substructure, extra connection points.

SWOT

Strengths	Environmental benefits: sustainable, no need for nutrient input or waste management. Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. No need for extra connection points/buoys & anchorage outside substructure
Weaknesses	Environmental impacts depend on scale (high seaweed production may lead to nutrient depletion). Forces on system from under water structures/ropes (higher maintenance costs substructures). Lower light levels in between substructures. Less space for suspension systems (relative to outside substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Threats	Distance to costumer. Competition with inshore seaweed farms. Exposure to weather, severe storms

16. Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae - Between substructures

Description of system

Closed Containment Aquaculture System (CCAS)	Closed containment (in double wall tubing system) in situ (in seawater), inoculation module on platform, production as floating module between the substructures (fixed connection), controlled conditions.
Positioning in relation to substructures	Between substructures
Main product	Microalgae
Proposed location	Mediterranean Sea (off shore)

Main requirements & characteristics

Means of production	Seawater, inoculation biomass on platform, production of microalgae on floating modules between the substructures, expert labour, CO2 supply, nutrients, power supply
Facilities	On the platform: O&M, processing, harvest (e.g. centrifuge), storage (e.g. freezer), cultivation system for inoculation material of microalgae Between the substructures: floating production modules for microalgae biomass
Conditions	Ensuring of stable production because of consistent supply of inoculation material on the platform, Stable culture temperature by means of submerged conditions of tubing system, additionally, equally light distribution and dilution
Transport & logistics	Transport and storage of feed and product (microalgae biomass) between mainland and platform, operation of floating modules takes place on platform
State of the art	No comparable system available
Time to implementation	Mid-term
Depth location	About 1 to 2 m water depth required for operation of floating production modules
Metrics substructure	Specific design to ensure an appropriate connection to floating modules (power-free, impulse-free transmission)

SWOT

Strengths	Operation of floating module takes place on platform; use of mechanical forces for mixing and seawater temperature for maintaining growth temperature of microalgae suspension; low (electrical) energy input for production in floating modules; continuous production ensured due to stable input of fresh inoculum from defined platform system; low impact on environment (closed system), no expensive rack for installation needed
Weaknesses	Hard to scale up; possible shading effects because of platform and buildings on them; dependency of culture temperature on seawater temperature. More complex design of entire platform system; as well as building structure as also facilities on top of them; size of floating module depends on platform size and is reduced compared to "free" application
Opportunities	Access to seawater Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Reduction of energy demand for microalgae production (mixing, cooling).
Threats	Dependent on nutrient supply from mainland. Competition with onshore production. Biological impact on environment has to be assessed.

17. Factsheet Closed Containment Aquaculture System CCAS: Fish - connected OUTSIDE substructures

Description of system

Closed Containment Aquaculture System CCAS	Large partly submerged, floating enclosures in situ (in seawater). Enclosures may be are connected to substructure, controlled water flow in and out of the enclosures . Treatment of intake and discharge water.
Positioning in relation to substructures	connected OUTSIDE substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power.
Facilities	Enclosures, moorings to sea floor, pre-treatment of intake water, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Recently established technology. Various variants by different companies. The technology is expected to advance further in the near future
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Low energy demand compared to RAS and FTS. Treatment of intake water; low risk of pathogen intake Advancing technology. No escapes
Weaknesses	Recent technology, may not be fully established. Environmental claims not yet fully documented Technically more complex than traditional sea cages Environmental impacts from fish waste Forces on system from under water structures/ropes (higher maintenance costs substructures).
Opportunities	Sheltered location close to substructures Controlled discharge of solid wastes Operation from substructure; no need for large vessels (feed barge, well boats). Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

18. Factsheet Cage Aquaculture System : Fish - connected OUTSIDE substructures

Description of system

Closed Containment Aquaculture System CCAS	Large d, floating netpens or cages in situ (in seawater). Cages may be are connected to substructure,
Positioning in relation to substructures	Connected OUTSIDE substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power
Facilities	Cages , moorings to sea floor, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Established technology.
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand compared to RAS and FTS. Established technology.Low production costs compared to other aquaculture systems No need for extra connection points outside substructure.
Weaknesses	Environmental impacts from solid waste and escapes Limited control over water quality Substructure blocking water currents required for water exchange cages.
Opportunities	Sheltered location close to substructures Mooring to substructure Operation from substructure; no need for large vessels (feed barge, well boats). Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

19. Suspension Culture System: Shellfish - connected OUTSIDE substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) ropes are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	Connected to OUTSIDE substructures
Main product	Shellfish
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, feed, mussel seeds, harvesting & maintenance requires labour and depending on harvest method may require electricity.
Facilities	O&M aquaculture building on substructure, harvesting units, processing plant (optional), energy supply low, diving activities (automated).
Conditions	low or high current, environmental oxygen & seawater, unstable conditions (weather dependent), limited shelter/wave protection.
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Shallow water (between 10-20m)
Metrics substructure	Mass below substructure, extra connection points.

SWOT

Strengths	Environmental benefits: increased water clarity (filtration, but see carrying capacity overriding risk), increased biodiversity. Technically simple, not sensitive to technical failure. Relatively low maintenance, low energy demand, low cost on production. Established and advancing technology. Reduction of buoys and anchorage outside substructure. More space for suspension systems outside substructures, larger scale cultivation possible. More use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Weaknesses	Environmental impacts depend on scale. The larger the scale the more chance of overriding the carrying capacity or impacting the benthic community (organic decomposition). Forces on system from under water structures/ropes (higher maintenance costs substructures).
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or wind parks (less applicable due to limited space availability). Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition mussel farms Wadden sea. Damage due to exposure to high seas, severe storms.

* specific for positioning: in between, inside, outside, on top (RAS)

20. Factsheet Suspension Culture System: Seaweed – connected to outside substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) but ropes are connected to substructures, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	Connected to outside substructures
Main product	Seaweed
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, seedlings, harvesting & maintenance requires labour and depending on harvest method may require electricity
Facilities	Potential storage O&M aquaculture building, harvesting unit, seeding unit, potential processing (drying) factory, supply of energy, environmental seawater & CO_2 supply.
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units, assistance vessel. Transport of produce to the mainland.
Conditions	Reasonable to good light availability (some shading from substructures/buildings), low or high current, unstable conditions (weather dependent), limited shelter/wave protection.
Time to implementation	Short
Depth location	Shallow water (between 10-20m)
Metrics substructure	Mass below substructure, extra connection points.

SWOT

Strengths	Environmental benefits: sustainable, no need for nutrient input or waste management. Technically simple, not sensitive to technical failure. Relatively low maintenance, low energy demand, low cost on production. Established and advancing technology. Higher light levels outside substructures. More space for suspension systems outside substructures (relative to inside substructures).
Weaknesses	Environmental impacts depend on scale (high seaweed production may lead to nutrient depletion). Forces on system from under water structures/ropes (higher maintenance costs substructures). Depending on the scale of the farm decomposition of seaweed fragments may alter nutrient composition in the sea bottom below. Need for extra connection points/buoys and anchor points outside substructure.
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Threats	Distance to costumer. Competition with inshore seaweed farms. Damage due to exposure to high seas, severe storms.

* specific for positioning: in between, inside, outside, on top (RAS)

21. Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae – connected to outside substructures

Description of system

Closed Containment Aquaculture System (CCAS)	Closed containment (in double wall tubing system) in situ (in seawater), inoculation module on platform, production as floating module next to platform (fixed mechanical connection), controlled conditions.
Positioning in relation to substructures	Outside, connected to substructures
Main product	Microalgae
Proposed location	Mediterranean Sea (off shore)

Main requirements & characteristics

Means of production	Seawater, inoculation biomass on platform, production of microalgae on floating modules next to platform, expert labour, CO2 supply, nutrients, power supply
Facilities	On the platform: O&M, processing, harvest (e.g. centrifuge), storage (e.g. freezer), cultivation system for inoculation material of microalgae Next to platform: floating production modules for microalgae biomass
Conditions	Ensuring of stable production because of consistent supply of inoculation material on the platform, Stable culture temperature by means of submerged conditions of tubing system, additionally, equally light distribution and dilution
Transport & logistics	Transport and storage of feed and product (microalgae biomass) between mainland and platform, operation of floating module via the connection to platform
State of the art	No comparable system available
Time to implementation	Mid-term
Depth location	About 1 to 2 m water depth required for operation of floating production modules
Metrics substructure	Specific design to ensure an appropriate connection to floating modules (power-free, impulse-free transmission)

SWOT

Strengths	Use of mechanical forces for mixing and seawater temperature for maintaining growth temperature of microalgae suspension; low (electrical) energy input for production in floating modules; continuous production ensured due to stable input of fresh inoculum from defined platform system; low impact on environment (closed system), no expensive rack for installation needed, no expensive rack for installation needed
Weaknesses	Transport of harvest material between floating module and platform. Dependency of culture temperature on seawater temperature. Need for extra connection points/buoys and holdfast (anchorage) outside platform to secure rigid connection. More complicated to scale up because of required connection.
Opportunities	Access to seawater Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Reduction of energy demand for microalgae production (mixing, cooling).
Threats	Dependent on nutrient supply from mainland. Competition with onshore production. Biological impact on environment has to be assessed.

22. Factsheet Closed Containment Aquaculture System CCAS: Fish - in PROXIMITY of substructures

Description of system

Closed Containment Aquaculture System CCAS	Large partly submerged, floating enclosures in situ (in seawater). Enclosures may be are connected to substructure, controlled water flow in and out of the enclosures . Treatment of intake and discharge water.
Positioning in relation to substructures	IN PROXIMITY of substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power.
Facilities	Enclosures, moorings to sea floor, pre-treatment of intake water, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Recently established technology. Various variants by different companies. The technology is expected to advance further in the near future
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Low energy demand compared to RAS and FTS. Treatment of intake water; low risk of pathogen intake Advancing technology. No escapes
Weaknesses	Recent technology, may not be fully established. Environmental claims not yet fully documented Technically more complex than traditional sea cages Environmental impacts from fish waste Forces on system from under water structures/ropes (higher maintenance costs substructures). Exposed, high energy locations
Opportunities	Controlled discharge of solid wastes Substructure as supply hub Off shore aquaculture production Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

23. Factsheet Cage Aquaculture System : Fish - in PROXIMITY of substructures

Description of system

Closed Containment Aquaculture System CCAS	Large, floating netpens or cages in situ (in seawater). Cages may be are connected to substructure,
Positioning in relation to substructures	in PROXIMITY of substructures
Main product	Fish
Proposed location	Mediterranean and Northern North sea

Main requirements & Characteristics

Means of production	Seawater, feed, juvenile fish, labour, electrical power
Facilities	Cages , moorings to sea floor, O&M aquaculture building on substructure, vessels, processing plant (optional), diving activities (automated). Feed storage and supply systems
Conditions	low or high current, environmental seawater
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, aquaculture in support vessels to transport feed and juveniles to and fish harvests from the enclosures. Transport of produce to markets on the mainland.
State of the art	Established technology.
Time to implementation	Short
Depth location	Deep water (60+m)
Metrics substructure	

SWOT

Strengths	Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand compared to RAS and FTS. Established technology. Low production costs compared to other aquaculture systems No need for extra connection points outside substructure.
Weaknesses	Environmental impacts from solid waste and escapes Limited control over water quality
Opportunities	Substructure as off shore maintenance & supply hub
Threats	Distance to market. High dependency on supply of means of production from the mainland. Competition Exposure to weather, severe storms.

* specific for positioning: in between, inside, outside, on top (RAS)

24. Suspension Culture System: Shellfish – in PROXIMITY of substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater) ropes are connected to substructure, no water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	In proximity of substructures (not connected)
Main product	Shellfish
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, feed, mussel seeds, harvesting & maintenance requires labour and depending on harvest method may require electricity
Facilities	O&M aquaculture building on substructure, seeding unit, harvesting units, processing plant (optional), diving activities (automated).
Conditions	low or high current, environmental seawater & oxygen supply, unstable climate conditions.
Transport & logistics	Supply of part of the means of production from the mainland, feed/produce storage unit (cold), crane units, assistance vessel, aquaculture in support vessels. Transport of produce to markets on the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Shallow (between 10 – 20m)
Metrics substructure	Standard

SWOT

Strengths	Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. More space available for larger scale production. Increase water clarity. Use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Weaknesses	Potential environmental impact from shellfish waste Forces on system from under water structures/ropes (higher maintenance costs substructures). Extra connection and anchor points needed.
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA, combination with seaweed reduces waste) or wind parks (less applicable due to limited space availability). Potential for livelihood & living in areas facing sea level rise (Pacific Islands).
Threats	Distance to costumer. Competition mussel farms Wadden sea. Damage from exposure to high seas, severe storms.

25. Factsheet Suspension Culture System: Seaweed – outside in proximity of substructures

Description of system

Suspension Culture System (SCS)	Suspension culture based in situ (in seawater). Ropes are not connected to substructures. No water demand or treatment but uncontrolled conditions.
Positioning in relation to substructures	Outside, in proximity but not connected to substructures
Main product	Seaweed
Proposed location	North sea (offshore)

Main requirements & Characteristics

Means of production	Seawater, seedlings, harvesting & maintenance requires labour and depending on harvest method may require electricity.
Facilities	Potential O&M building and harvesting units, processing factory (optional), environmental seawater & CO_2, diving activities (automated).
Conditions	Ample light availability (no shading platform and/or buildings), low or high current, unstable conditions (weather dependent), no or limited shelter/wave protection, WQ standards.
Transport & logistics	Supply of part of the means of production from the mainland, produce storage unit (cold), crane units, assistance vessel. Transport of produce to the mainland.
State of the art	Established technology which is expected to advance further in the near future.
Time to implementation	Short
Depth location	Shallow (between 10-20m)
Metrics substructure	Standard substructure

SWOT

Strengths	Environmental benefits: sustainable, no need for nutrient input or waste management. Technically simple, not sensitive to technical failure. Relatively low maintenance. Low energy demand. Established and advancing technology. Low cost on production. Higher light levels outside substructures. More space for suspension systems outside substructures. No forces on system from under water structures/ropes (higher maintenance costs substructures).
Weaknesses	Environmental impacts depend on scale (high seaweed production may lead to nutrient depletion) and decomposition of seaweed fragments may alter nutrient composition in the sea bottom below. Need for extra connection points/buoys/holdfast outside substructure.
Opportunities	Use of space in North sea (opposed to limited space available inshore and Oosterschelde). Combination with other aquaculture (IMTA) or windparks. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Use of suspended culture system to dampen wave energy & currents (lower maintenance costs substructures).
Threats	Distance to costumer. Competition with inshore seaweed farms. Damage due to exposure to high seas, severe storms.

* specific for positioning: in between, inside, outside, on top (RAS)

26. Factsheet Closed Containment Aquaculture Culture System (CCAS): Microalgae – outside in proximity of substructures

Description of system

Closed Containment Aquaculture System (CCAS)	Closed containment (in double wall tubing system) in situ (in seawater), inoculation module on platform, production as floating module next to platform (only electrical connection), controlled conditions.
Positioning in relation to substructures	Outside, in proximity but not connected to substructures
Main product	Microalgae
Proposed location	Mediterranean Sea (off shore)

Main requirements & characteristics

Means of production	Seawater, inoculation biomass on platform, production of microalgae on floating modules next to platform, expert labour, CO2 supply, nutrients, power supply
Facilities	On the platform: O&M, processing, harvest (e.g. centrifuge), storage (e.g. freezer), cultivation system for inoculation material of microalgae Next to platform: floating production modules for microalgae biomass
Conditions	Ensuring of stable production because of consistent supply of inoculation material on the platform, Stable culture temperature by means of submerged conditions of tubing system, additionally, equally light distribution and dilution
Transport & logistics	Transport and storage of feed and product (microalgae biomass) between mainland and platform, inoculation, feeding and harvest via detachable (not stationary) pipes and service ships
State of the art	No comparable system available
Time to implementation	Mid-term
Depth location	About 1 to 2 m water depth required for operation of floating production modules
Metrics substructure	No specific requirements (no (rigid) connection to floating modules)

SWOT

Strengths	Use of mechanical forces for mixing and seawater temperature for maintaining growth temperature of microalgae suspension; low (electrical) energy input for production in floating modules; continuous production ensured due to stable input of fresh inoculum from defined platform system; low impact on environment (closed system); almost independent operation from platform possible; easier to scale up compared to rigid connection, no expensive rack for installation needed
Weaknesses	Transport of feed/harvest material between floating module and platform. Dependency of culture temperature on seawater temperature. Need for extra connection points/buoys and holdfast (anchorage) outside platform.
Opportunities	Access to seawater Combination with other aquaculture (IMTA) or wind farms. Potential for livelihood & living in areas facing sea level rise (Pacific Islands). Reduction of energy demand for microalgae production (mixing, cooling).
Threats	Dependent on nutrient supply from mainland. Competition with onshore production. Biological impact on environment has to be assessed.