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Deliverable 3.3

Design and implementation of mariculture structures

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Abstract	This task focuses on advancing the design and attachment methods for innovative mariculture structures aimed at enhancing the cultivation of mussels, oysters, and seaweed. Building on the knowledge developed through the H2020 UNITED project, the task will explore optimal designs

	for various cultivation systems, such as nets, droppers, baskets, and lanterns. Key objectives include improving anti-fouling solutions, optimizing growth potential, and evaluating cost-effective seaweed nursery settings. Nearshore testing will be conducted in Task 4.1, with pilot leads contributing to the design and specification of these novel systems. The assembly and installation will be carried out by designated partners at each pilot site, with the results and innovations documented in this Deliverable D3.3.
Keywords	Mariculture structures, mussel culture, European flat oyster culture, seaweed cultivation, anti-fouling solutions, seaweed nursery, and installation methods

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Acronyms

ARC	Acoustic Release Canister
D	Deliverable
HMPE	High Modulus Polyethylene
NID	Nature Inclusive Design
PE	Polyethylene
WP	Work package

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Executive Summary

Deliverable D3.3 presents the outcomes of Task 3.3 within the ULTFARMS project, focusing on the **design and implementation of innovative mariculture structures** for seaweed, blue mussels, and flat oysters. The deliverable captures the iterative design process and technical development of cultivation systems suitable for offshore wind farm integration across six pilot sites in Belgium, the Netherlands, Germany (North and Baltic Seas), and Denmark (Baltic Sea). These designs represent advancements towards TRL 7, emphasizing resilience, biological efficiency, cost-effectiveness, and compatibility with offshore wind farm infrastructure.

Scope and objectives

The primary objective of Task 3.3 was to advance and compare mariculture structures adapted to offshore conditions. The work included design iterations for nets, droppers, lantern baskets, submerged lines, and anchoring systems, as well as antifouling innovations and optimizations in seeding and nursery strategies. This deliverable builds on knowledge from the H2020 UNITED project and integrates co-design processes with stakeholders and technical partners.

Methodology and testing

Designs were developed in close collaboration with WP3 partners and tested through nearshore trials (WP4) and in some cases, offshore deployment. Structures were evaluated for biological performance, system durability, ease of handling, and suitability for large-scale implementation. Each pilot contributed site-specific adaptations based on local environmental conditions, logistical realities, and species targeted.

Key results by species and design

- **Seaweed (*Saccharina latissima, Palmaria palmata, Ulva and Alaria esculenta*):** Both Danish and German pilots focused on suspended net or dropper systems. In Denmark (Anholt), submerged longlines and droppers were trialled with varying pre-seeding methods. In Germany, direct seeding on horizontal nets outperformed twine-based methods in early trials. Submersible net systems were also piloted in the Belgian site.
- **Blue mussels (*Mytilus edulis*):** Optimized collector types (e.g. belt vs loop) and mussel line configurations were trialled in Danish, Dutch, and German sites. At FINO3, a robust offshore system with high survival and favorable flesh-to-shell ratios was validated under harsh winter conditions.
- **Flat oysters (*Ostrea edulis*):** Multiple cultivation structures were trialled at the Belgian pilot, including SEAPA basket frames, ropes with cemented oysters, and heavy metal cages. The SEAPA frames showed the best performance in terms of biofouling management and structural integrity.

Pilot-specific highlights

- **German North Sea Pilot (FINO3):** Demonstrated success of robust mussel and seaweed systems. The longline infrastructure proved resilient against winter storms. Strong integration with monitoring (lander-based sensors) and antifouling trials. Notable for synergies with nearby wind farm operations.
- **German Baltic Sea Pilot (FINO2):** Focused on modular, multi-use monopile-based designs, integrating seaweed and nature-inclusive elements.
- **Dutch Pilot (Borssele):** Deployed a Smart Mussel Farm (SMF) system with integrated sensor technology. Feasibility studies on power supply and real-time monitoring were incorporated. Mussels will undergo taste testing under WP5.
- **Danish Pilot (Anholt):** Trialled droppers and submerged longlines for two seaweed species. Variations in attachment and pre-seeding were compared. Demonstrated that anchoring and mooring are major variables for performance.
- **Danish Pilot (Samsø):** Tested mussel grow-out structures on floating tubes, complementing the submerged configurations at Anholt.
- **Belgian Pilot (Belwind):** Developed and tested a submersible seaweed system and diverse oyster grow-out structures offshore. Nearshore pre-testing proved critical. Lessons learned informed mooring design improvements and highlighted the need for flexible and modular setups. Results feed into D3.5 and WP6/WP10.

Cross-pilot insights and WP integration
Common lessons across pilots include the importance of pre-operational nearshore testing, the need for redundancy and flexibility in mooring systems, and the trade-offs between robustness and operational efficiency. The deliverable integrates with:

- **WP4** for offshore deployment and validation;
- **WP5** for economic feasibility;
- **WP6** for environmental monitoring;
- **WP7** for potential reef effects and nature-inclusive design;
- **WP9** for regulatory insights from permitting processes;
- **WP10** for the roadmap toward large-scale, multi-use offshore aquaculture.

Contribution to ULTFARMS roadmap
D3.3 provides key technical inputs for the final design selection and implementation strategy of ULTFARMS. It contributes foundational knowledge on system performance, anchoring reliability, and cultivation success. These insights are critical for defining best practices for scaling mariculture within offshore wind farms across Europe and inform replication strategies under WP10.

In summary, D3.3 represents a comprehensive synthesis of design development for offshore mariculture. It advances technical readiness across pilots and supports the broader ambition of ULTFARMS to establish sustainable, low-trophic aquaculture as a viable offshore sector integrated with renewable energy infrastructure.

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1. General Introduction

1.1 Description of the project

The ULTFARMS project aims to move beyond the current application of Low-Trophic Aquaculture (LTA) systems with novel engineering, technical, ecological and biological processes to optimise production in harsh offshore conditions, low salinities, and their integration within Offshore Wind Farms (OWFs). ULTFARMS will cover the whole value chain expertise for LTA production in OWFs. The project works with research and industry partners to develop and operate six innovative Low-Trophic Aquaculture Pilots (LTAPs) in six different OWF locations across the North Sea and Baltic Sea.
These six pilots are implemented in the following areas (*Table* 1):

Table 1: Overview of the six LTA pilots of ULTFARMS.

Member state	Name of OWF	LTA production
Belgium	Belwind	Seaweed -Oysters
The Netherlands	Borssele	Blue mussels
Germany	FINO2	Seaweed
Germany	FINO3	Seaweed-Blue mussels-Oysters
Denmark	Anholt	Seaweed-Blue mussels
Denmark	Samsø	Seaweed-Blue mussels

1.2 Objective of task 3.3

This deliverable reports on task 3.3 of ULTFARMS: Design and attachment methods for innovative mariculture structures/systems for blue mussels, oysters and seaweed (to TRL7). The objective is to advance the design and attachment methods for innovative mariculture structures, improving anti-fouling solutions, optimizing growth potential, and evaluating cost-effective seaweed nursery settings.

1.3 Knowledge and recommendations from previous H2020 UNITED project

This deliverable builds on the developed knowledge from previous projects such as the H2020 UNITED project for seaweed, blue mussel and oyster culture.

The Belgian and German Pilot continued their activities from UNITED to ULTFARMS, allowing implementation of lessons learned.

For a full description of the systems we refer to UNITED (https://cordis.europa.eu/project/id/862915/results) D.7.1 (Review of pilot TRL, legal aspects, technical solutions and risks), UNITED D7.2 (Blueprint for the offshore site operation), D7.4 (Joint production, monitoring, operation and maintenance protocol) and D7.7 Synthesis report for pilots.

In short for the **Belgian Pilot** of UNITED, seaweed cultivation, oyster culture and oyster restoration efforts were combined with wind energy production. Different parameters and cultivation techniques were tested in a nearshore site. In 2022, two separate longline systems were installed in the offshore Belwind site: one system for oyster cultivation and the other for seaweed cultivation. Several different types of cultivation structures were dispersed along the oyster backbone to determine best practices for oyster grow out offshore. The seaweed longline used a net system for grow out and tested two different seeding methods of sugar kelp (*Saccharina latissima*). **Both lines were retained for the ULTFARMS project.** The UNITED Belgian pilot also conducted a feasibility study for oyster restoration by installing four restoration tables on the sea floor in the Belwind concession area. We refer for more details to UNITED D7.7 "Synthesis report for pilots".

Lessons learned regarding system design and implementation from UNITED for the Belgian site:

- It is crucial to ensure that the infrastructure can withstand the harsh conditions of the site. Modelling is an essential tool for this, but it should be supplemented and validated by the experience of industry members who can provide practical advice, which was done so in the preparation of going offshore. We refer for more details to UNITED D7.7 "Synthesis report for pilots".
- The preoperational nearshore tests were essential for identification and development of suitable cultivation techniques for oyster and seaweed aquaculture and restoration offshore. Trial and error were necessary to determine the most effective methodologies (e.g. seeding techniques, substrates and net material) and revise designs for the offshore environment. We refer for more details to UNITED D7.7 "Synthesis report for pilots".

Within the **German pilot** of UNITED, seaweed (*S. latissima*) and blue mussel cultivation (*M. edulis*) have been adapted in iterative loops for offshore aquaculture at an exposed location. The cultivation systems were installed next to the FINO 3 research platform, 80 km off the German coast in the German EEZ, adjacent to two windfarms. Additional to the two longline systems a lander, entailing various in-situ sensors for system performance and environmental data was deployed. The general deployment and decommissioning were successful and allowed for vital insights both into system performance and cultivation methodologies. Various multi-use aspects were investigated and synergy effects developed. In addition, multiple cultivation tests and anti-fouling trials were carried out nearshore.

Several examples of lessons learned regarding system design and implementation from UNITED for the **German pilot** site are (further details can be found in UNITED D7.7 "Synthesis report for pilots"):

- During the operational phase of the offshore aquaculture multi-use project, specific needs and challenges associated with the project site were identified. These factors played a crucial role in shaping the project's approach and outcomes. Ship (un)availability and the short-term nature of weather forecasts required strong permanent commitment of the employees like, partly 24h standby and permanent research for available ships and alternatives. This led to increased ambitions to create additional synergy effects with other offshore users of the location or nearby wind parks. Weather forecasts and site-specific experiences with them were more closely exchanged, offshore personnel were trained to cover some maintenance activities. New opportunities and limits for these cooperations were discovered as an outcome.
- System Resilience: Despite challenging offshore conditions characterized by strong currents and high waves, the mussel system demonstrated resilience and successfully withstood winter storms. Contrary to the major skepticism of stakeholders at the beginning of the project, this is a huge success. This underscored the importance of designing aquaculture systems to withstand harsh environments and incorporating resilience features into system design. Nevertheless, adaptations towards lighter and smaller components are needed.
- Equipment malfunctions and accidents: An equipment malfunction resulted in interrupted or failing monitoring. These incidents emphasized the significance of thorough equipment testing, regular maintenance, and quality control measures to minimize the risk of accidents and equipment failures. The ship crews became more and more familiar with handling offshore aquaculture equipment and the installation procedure. Experienced and established ship crews increase safety and accelerate the time of offshore installations. The setting up of such teams is highly recommended and could be a competitive advantage in the offshore market if multi-use is expanded in the future.

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In the below subsections **key knowledge and recommendations regarding design of mariculture systems and structures built up during the UNITED project are referenced per species.**

Seaweed culture

At the **German pilot** the net system for seaweed cultivation has been successfully deployed and decommissioned. The setup allowed for testing of different seeding methodologies and materials, being "twine" seeding and "direct" seeding on different lines. The subsequent harvest resulted in a total of 14 samples for detailed growth measurements of the macroalgae blades. The first growth trial indicated that the direct seeding technique of the net outperformed the twine seeding technique on the droppers. However, to optimize growth rates repeated testing with increased standardization efforts will be needed to finalize the interpretation.

Key lessons learned: Seaweed setup

- Although functional, the current net setup needs two operating vessels for its deployment and deinstallation. System adaptations may result in a more straightforward operation.
- Currently, there are few commercial seaweed companies operating in Europe. Knowledge of efficient methodologies is rare and professional equipment for the seeding and harvest procedure is limited and expensive.
- Due to external factors (e.g., weather), ship deployments may be interrupted or halted. This may be detrimental to juvenile seaweed. If the operation is interrupted, the execution of an already developed, alternative (storage) plan is vital.

In the Belgian Pilot seeding of *Saccharina latissima* was tested using the optimized 2-step direct seeding approach. The optimized 2-step direct seeding, where juvenile seaweeds are sprayed onto the cultivation substrate first and then covered with a layer of AlgaeBinder (AtSeaNova) resulted in improved seed retention in comparison to the direct seeding, where the AlgaeBinder is not sufficient to prevent loss of majority of juvenile seaweeds.

Mussel culture

At the **German pilot** the mussel system was successfully deployed and deinstalled. The growth data indicates good growth rates with higher flesh to shell ratios than in nearshore settings. The deployed mussel growth substrate indicated interesting patterns of mussel growth. This highlights potential scaling opportunities.

- The growth substrate had a great impact on the biomass generation, further testing to fine-tune the material is needed to provide the best cultivation methods.

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- Initially, so called "pencil-shaped" buoys have been deployed, these were specifically designed for offshore usage. Unfortunately, the original supplier went bankrupt, and replacements were needed. It has been proven essential to have extensive networks, as specific compounds may be difficult to obtain.

Oyster culture

Flat oysters were successfully cultivated in the offshore **Belgian pilot** site during the UNITED project, and a comparison of four different cultivation structures yielded useful results. Cylindrical lantern baskets, ropes with oysters cemented, heavy metal cages, metal frames each containing 4 SEAPA baskets were distributed along the longline system. Survival rates were high across all cultivation methods except for the ropes. Clear differences were noticed between the different structures in terms of structural integrity, biofouling, and influence on shell morphology. **Among these options, the frames containing SEAPA baskets appeared to be the best combination of low internal biofouling, higher structural integrity, and practical convenience.**

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2. Design and attachment methods for innovative mariculture structures

2.1 Seaweed

2.1.1 Danish pilot(s) design

There are two Danish pilot cases: Anholt and Samsø (Figure 1). The farm setup in Anholt is based on submerged long lines, whereas the setup in Samsø is based on floating tubes. The Anholt farm is the only of the two pilots where seaweed will be farmed.

Figure 1: Location of the two Danish pilot sites.

Anholt:

The longlines are 130 m in length and submerged to 5 m using 35 kg concrete blocks at the bottom (every 10-20 m) and 7 l buoys along the longline (*Figure* 2). Both blocks and buoys are tied to the long line using 16 mm 3-strand PE rope. At each end of the longlines, two 250 L end buoys are installed. At the bottom, the lines are installed with a 1T Danforth anchor and 30 meters of 40Ømm chain (40 kg/m) (Figure 3) followed by 30 m 36 mm 3-strand rope in each end. The long line itself is a 36 mm polysteel rope. 3 longlines have been installed for the project.

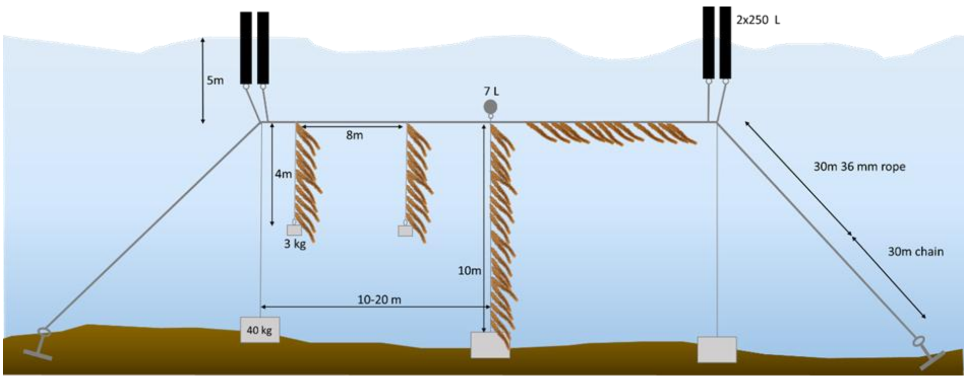

Figure 2: Schematic drawing of the longline farm structure in Anholt.

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Figure 3: Picture of anchors and anchor chain.

Two species of seaweed (*Saccharina latissima* and *Palmaria palmata*) are currently farmed at the Anholt site. In season 2023-2024, different seaweed line setups are being tested (*Figure 2*) for both species. During deployment, pre-seeded lines with a diameter of 4-8 mm were either fastened to the main line, the block rope, or deployed vertically as droppers from the main line. For those attached to the main line and block rope, the pre-seeded line was wrapped around the rope and secured with knots at both ends. For the droppers, the lines were simply tied to the main line with a knot and kept vertical by a 1-liter concrete block at the bottom.

2.1.2 German pilot(s) design

The cultivation of algae takes place in both German pilots. The North Sea pilot at FINO 3 uses a net system, while the Baltic Sea pilot at FINO 2 uses a modular multi-purpose system on the monopile.

North Sea pilot (FINO 3):

The system on the German North Sea pilot for cultivating algae is a net system with a total extension of approx. 250 meters from anchor to anchor. The overall set up can be seen in Figure 4.

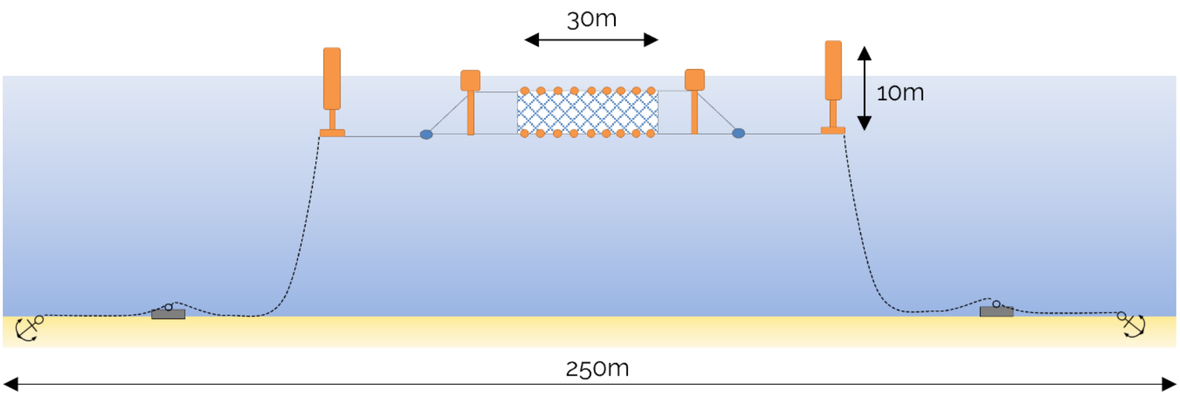

Figure 4: Layout of the algae system at the German North Sea pilot

The net is 30 m long and attached at both sides to 4m long spreader beams. Floaters are attached at the top of the net to provide the necessary buoyancy. On the lower edge, sinkers ensure stable orientation of the net in the water column. Spreader beams on both sides ensure that the net remains fully expanded in different wave and weather conditions. Each spreader has a net buoyancy of 150 kg.

As a safety measure a 45m long High Modulus Polyethylene (HMPE) rope, sheathed to prevent chafing, connects the two spreaders at the bottom side of the net, to prevent system breakage in the unlikely event of fatal damage to the net.

The upper and lower edges of the net on both sides of the system are connected with connection ropes to the so-called triplates. From the triplates, connection ropes lead to the Spar buoys. Each triplate has a diameter of 290 mm and weighs about 25kg. Except for the upper connection ropes leading from the net edges to the triplate, all ropes have a diameter of 28 mm and consist of HMPE. The upper connection ropes are slightly smaller.

The spar buoys, which can be seen in Figure 5 have a diameter of 0.9 m and provide the necessary buoyancy for the entire system. They carry the weight of the mooring chain and, with a total height of 10 m and 2.30 m above the waterline, they are clearly visible even in high waves. These buoys can also be deployed independently without the net, so that the net can be removed or attached later. This increases the flexibility of the system. The spar buoys have two hoisting points each to lift them out of the water for removal or installation of the net.

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Figure 5: Spar buoys of the algae system

Mooring chains (48mm diameter stud link chains) with a length of 75m connect the Spar buoys to 6t concrete blocks (Figure 6) deployed on each side of the system on the seabed. Each block is connected by a 50 m chain to a delta flipper anchor. This setup ensures that only horizontal drag forces are transferred to the delta flipper.

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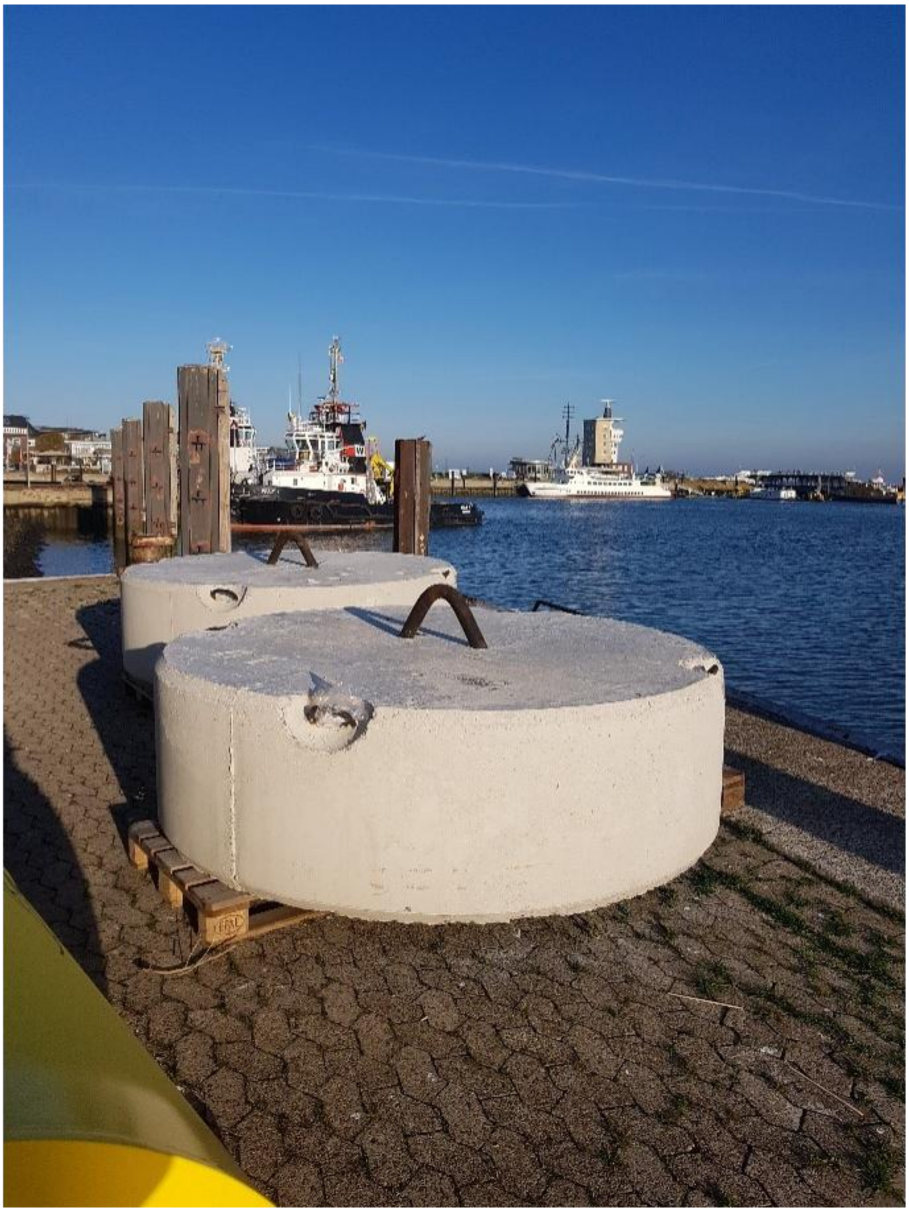

Figure 6: Six ton concrete block for mooring of the algae system

Baltic Sea pilot (FINO 2):

For the German Baltic Sea pilot a modular, compact system has been developed to harmonize with wind park requirements, that is applicable to most monopile structures. In addition this system can be set up for a variety of purposes. The system was used for the installation of macroalgae cultivation, but also to test a nature inclusive design solution. The systems backbone is one and a half meters in height and one meter in width. The backbone can be adapted to house for example algae lines or the growth substrate for nature inclusive design studies. Two systems, one for algae cultivation and one for nature inclusive design were deployed at two depths at the FINO2 monopile. The upper-most frame was used for macroalgae production and installed at a depth of minus three meters (Figure 7 left) The second design version for nature inclusive design (Figure 7 right) was deployed in deeper, calmer waters at ten meter depth. The systems installation procedure has been outlined in deliverable D4.2.

The base material of the backbone is standard stainless steel, which endures the corrosive environment for prolonged periods of time. zink-annodes were incorporated to prevent corrosion. The system design of the nature inclusive design version has been adjusted to meet the needs of juveline fish of the south western Baltic Sea, see also Deliverable D7.2 for further details.

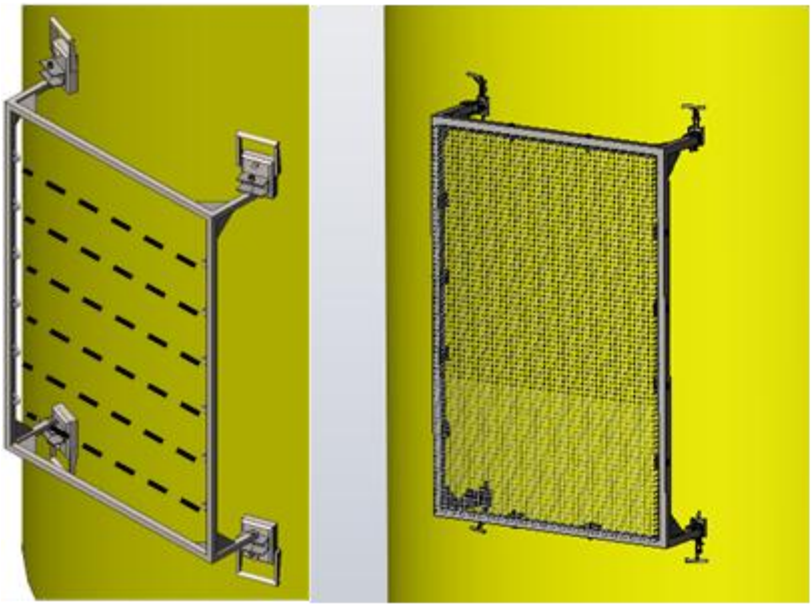

Figure 7: System designs of the German Baltic Sea pilot installation at FINO2. Left side: setup for macroalgae cultivation, right side, setup for nature-inclusive design.

2.1.3 Belgian pilot design

The seaweed cultivation lines were deployed at the southern end of the seaweed licence at Bantry Marine Research Station. The deployment location is approximately N 51.650, W -9.582 with the line oriented along an ENE-WSW axis.

The net design (Figure 8) was undertaken by the University of Ghent together with Impact-9. We refer to D3.2 for a general arrangement of the design for the seaweed systems. The positioning of 6 nets is as shown in Figure 9, the net defined as in Table 2. The anticipated total suspended weight in seawater is estimated to be 5.7 kg/m, but this depends on the level and type of biomass accumulation, where mussel accumulation could result in denser heavier biomass. The beam has

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been sized based on suspending 6kg/m wet weight over 30m length. Submergence will be possible for suspended weights in the range of 3kg/m (before biomass accumulation) to 6 kg/m (after biomass accumulation), considering a "normal operating pressure" of 0.6 bar will provide sufficient buoyancy to suspend the 6kg/m weight near the surface. Operating at lower pressures will yield additional buoyancies up to 9 kg/m but this should be seen as an operating margin to re-surface the line in the event of excess biomass accumulation, etc. For suspended weights exceeding 7kg/m, additional fixed flotation should be attached to the beam.

Nets were seeded with *Alaria esculenta* (strain: b2 Geurkiesfarm; 3 nets) or *Saccharina latissima* (strain: Ballyrisode; 3 nets) at two different gametophyte densities. Gametophyte stocks were estimated at 30.000 gametophytes/ml and 48.900 gametophytes/ml for *Alaria* and *Saccharina*, respectively. Direct seeding involved spraying of gametophytes at a dilution of 1/100 or 1/25 for low and high density, respectively. Following seeding, a glue cover (AlgaeBinder™) was applied at 2 L per net following manufacturer's instructions.

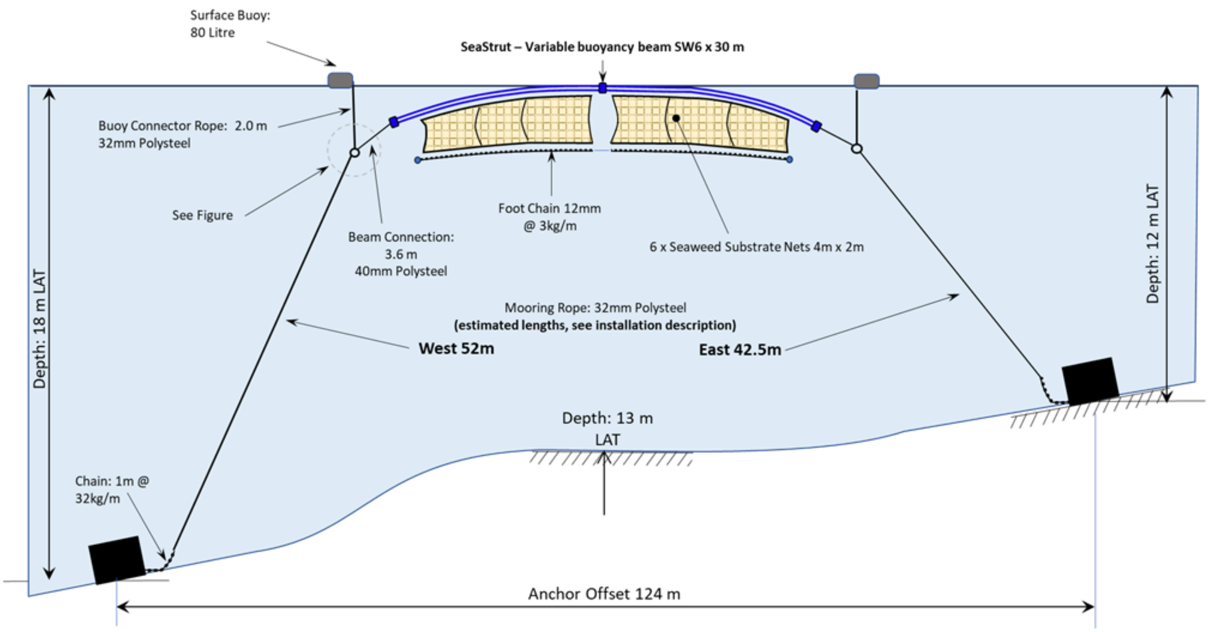

Figure 8: Layout of the seaweed cultivation system at Bantry Marine Research Station

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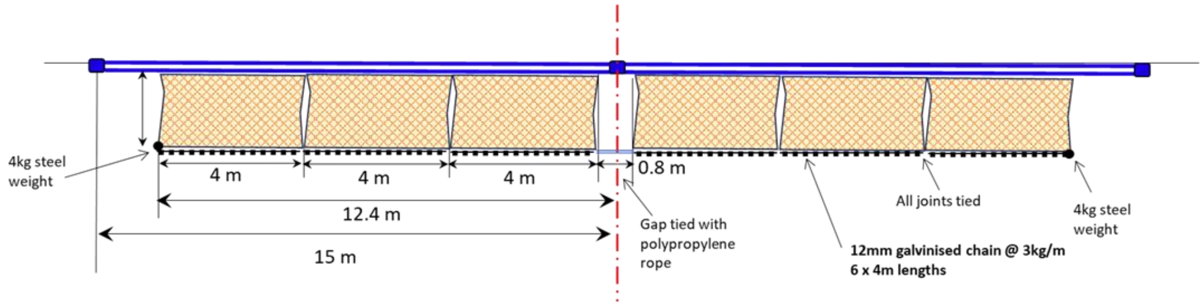

Figure 9: Positioning of 6 substrate nets on the beam as installed

Table 2: Net Properties as deployed at Bantry Marine Research Station.

Number of Nets	[-]	6
Length Depth	[m] [m]	4 2
Substrate Spacing	[mm]	200
Total net rope length	[m]	80
Substrate Diameter (incl biomass)	[mm]	25
Substrate Density (incl biomass)	[kg/m^3]	1300
Depth	[m]	2
Length	[m]	4
Total Mass (in air)	[kg]	51
Weight (in seawater)	[kg]	10.8 (2.7 kg / m)
Foot Chain	[kg/m]	3.0 kg / m

2.2 Mussels

2.2.1 Danish pilot(s) design

Mussel farming will be carried out in both pilot sites, using two systems: mussel longlines in Anholt (described in the section 2.1.1 on seaweed) and mussel tubes and nets in Samsø. We refer to ULTFARMS deliverable 3.2 for the design descriptions.

Anholt:

The mussel farming in Anholt will rely on natural spat settlement. For this, different types of spat collectors will be tested in different depth intervals. All collectors will be deployed as continuous loop systems. In Figure 10 different versions of spat collectors that will be tested during spring 2024 are shown. Longline setup was

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identical to the description in section 2.1.1, except for the use of 250L buoys along the mainline at distance intervals according to biomass accumulation (i.e. 5-15m). Three types of mussel spat collectors were deployed in 3-m continuous loops: Standard belt collector with 500g weight, Loop Spat Rope 9R (Quality Equipment, New Zealand), and Mega Loop Catch and Grow 9R (Quality Equipment, New Zealand). The longline configuration is represented in *Figure* 11,

Figure 10: Examples of types of spat collectors that will be tested in Anholt for mussel recruitment. Standard belt collector (left) and Mega Loop Catch (right).

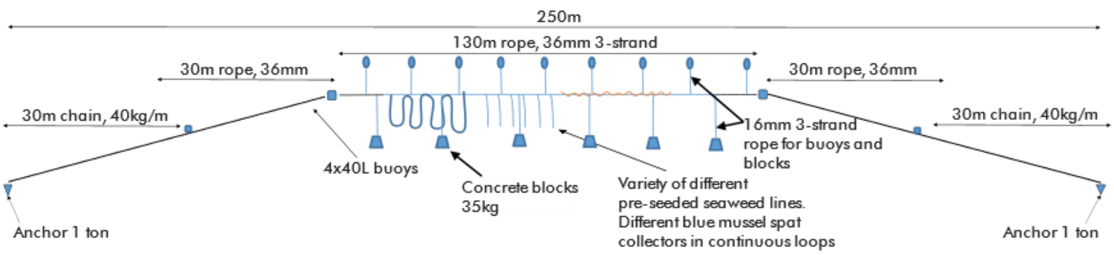

Figure 11: Longline configuration

<u>Samsø:</u>

In Samsø, standard SMARTFarm tubes and nets will be implemented and tested for mussel farming in the area. The tubes and nets were deployed in spring 2024.

The tubes are 130 m long with a diameter of 315 mm and a wall thickness of 10 mm (Material: PEH). Each pipe is anchored with a 1.2T anchor and 45 m of 40Ømm chain (40kg/m) followed by 40 m of 40 mm 3-strand rope in each end. Between the tube and the anchoring rope there is a line of 4 40 l buoys (*Figure* 12). 2 tubes have been installed for the project with a spacing of minimum 30 meters (*Figure* 13).

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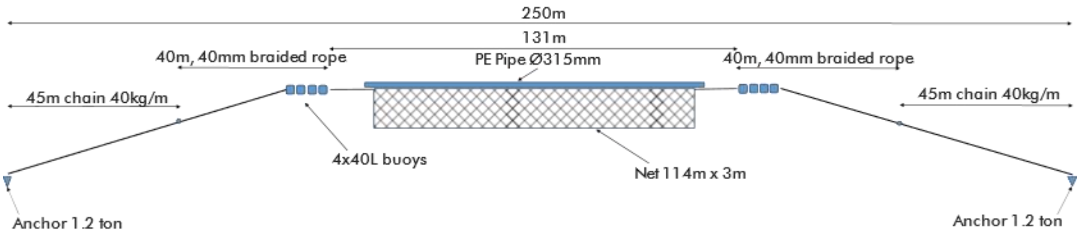

Figure 12: Schematic drawing of the tubes and net farm structure in Samsø.

Figure 13: Tubes deployed at site.

2.2.2 German pilot(s) design

<u>North Sea pilot (FINO 3):</u>

Blue mussels are cultivated using a submersed tube system (Figure 14) with a net-system. The tube, which is the backbone of the system, has a total length of 40 m and a diameter of 315mm. It is made of Polyethylene (PE) with a wall thickness of approximately 20mm. Empty, the tube weighs approx. 700 kg. When in use, it is filled with water and weighs approx. 3 tons, when fully filled.

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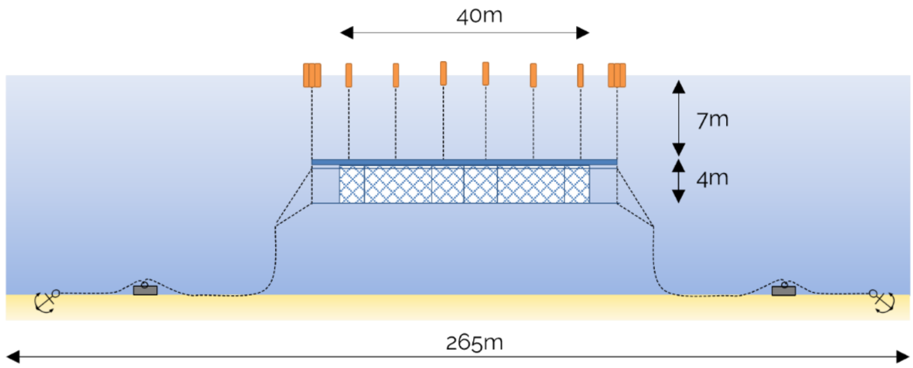

Figure 14: Layout of the mussel system at the German North Sea pilot

The net is attached directly to the tube. It consists of four different types of nets woven together to form a total net-length of around 24m with a height of four meters. The different net types and their arrangement can be seen in Figure 15 and Table 3.

Table 3: German North Sea Pilot net configuration

	Net size	Mesh size
Type 1	6,66m x 4m	90 x 90 mm 210/600 - Polypropylene 3mm thick and 12mm wide yarn
Type 2	6,66m x 4m	135 x 135 mm 210/500 - Polypropylene 3mm thick and 6.5mm wide yarn
Type 3	6,66m x 4m	200 x 200 mm 210/600 - Polypropylene 3mm thick and 12mm wide yarn
Type 4	2x 1,8m x 4m	200 x 200 mm - polypropylene “fuzzy” rope, core diameter 18mm expanded diameter 65mm

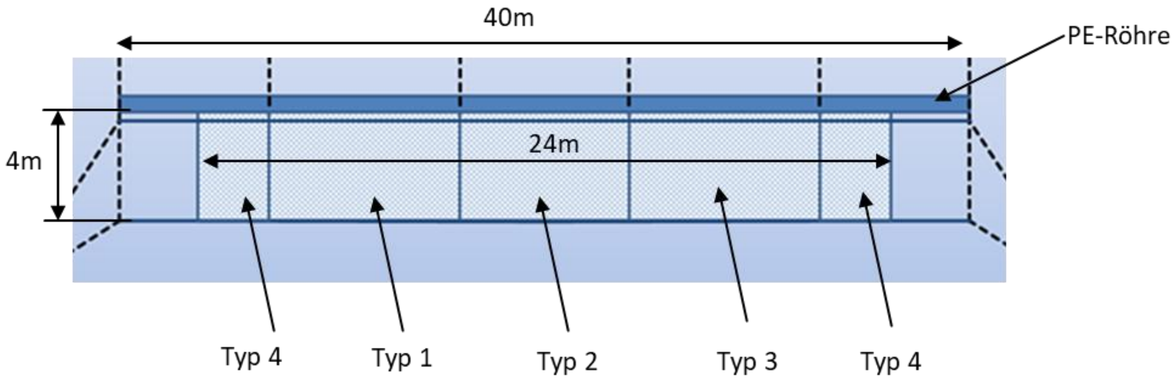

Figure 15: German North Sea Pilot mussel system net layout

The system is almost buoyancy neutral. It is pulled downwards by the weight of the anchoring chains. To keep the system stable at a depth of 7m, a total of 12 spar buoys are connected with chains to the backbone and provide the necessary positive buoyancy. The foam-filled polymer spar buoys have a diameter of 300 mm, a length of 4 m and a volume of 250l each.

The buoys are attached to the backbone using 13 mm chains (6.35 m each) and corresponding shackles. The attachment point is a stainless-steel bolt with an eye for shackling the buoy chains. This is inserted through the PE tube and crimped on the other side of the tube with a washer and sleeve.

The mooring is designed in the same way as the mooring of the algae system at the German North Sea pilot (see above). Only the chains from the concrete block to the mussel cultivation system are dimensioned smaller with a diameter of 19 mm (compared to 48mm in the algae system) to make the system lighter and ensure sufficient buoyancy.

In the course of the project, some support buoys were replaced. The new buoys, with a slightly different shape but the same volume, were attached to the same attachment points on the tube (Figure 16).

Figure 16: Adapted new buoys (black) and old buoys (yellow) at offshore site

2.2.3 Dutch pilot design

The Semi Submersible Mussel Farm was designed by OOS before the start of the ULTFARMS project. Thus, design of the system itself is not part of ULTFARMS. However, power management and monitoring and measurement is. The SMF is placed in Borssele wind park located about 55 kilometres from the Port of Vlissingen, The Netherlands, consisting of four major areas, of which sections III

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and IV are owned and operated by the consortium Blauwwind (Figure 17). The multiuse planning for these two areas includes a section dedicated to the integration of aquaculture within the wind park. This is the location where the test scale Submersible Mussel Farm (SMF) is deployed within the project activities (Figure 18). This system utilizes a semi-submersible platform as a central point from which the cultivation longlines run. This central platform serves as the connector point and can remain almost fully submersed in order to guard the aquaculture lines from the harsh environment. The unique line deployment system to be implemented in this configuration is relatively denser than many existing configurations. The test SMF consists of a 10x10 m platform with large horizontal pipes (white and blue in picture) that can be filled with seawater to adjust buoyancy. On one side 5 longlines of 200 m are attached. The Borssele pilot combines various sensors for monitoring information (Figure 19). For details see ULTFARMS Deliverable 3.2.

Figure 17: Location Windpark Borselle III

Figure 18: Test SMF being towed to location in Borssele windfarm and 2 longlines with loadcells.

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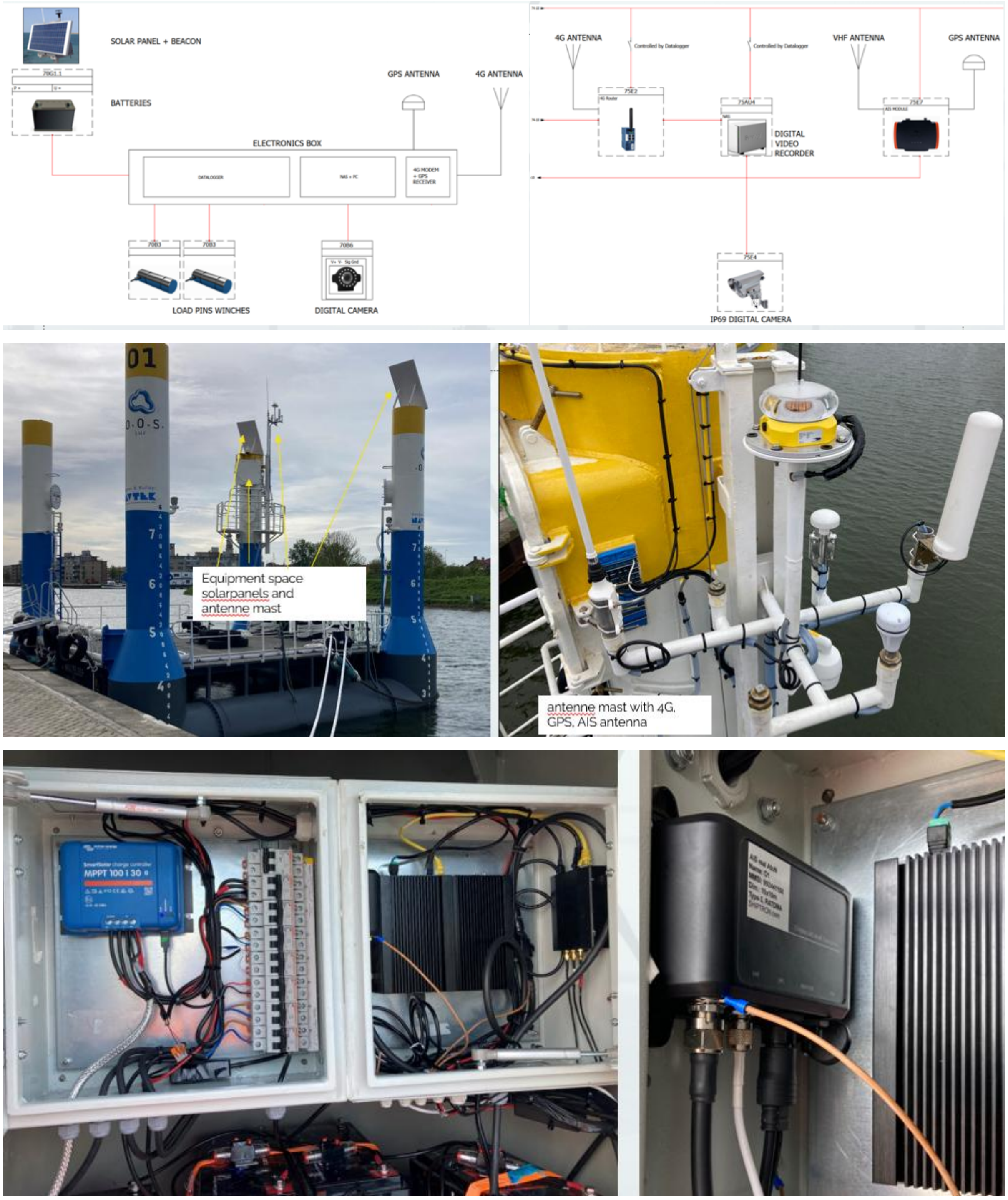

Figure 19: Electrical engineering of power and monitoring equipment.

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2.3 Oysters

2.3.1 German pilot design

North Sea pilot (FINO 3):

A specific Oyster cultivation system was designed and built for deployment at FINO3 in the North Sea. The system is placed on the seabed and is therefore unaffected by external weather influences. The process of deployment is described in ULTFARMS Deliverable 4.2.

The System is made of steel and consists of two sections (Figure 20). The lower part is made of a flat steel section and provides the necessary stability and strength for the entire structure. Steel legs are welded to each of the four corners. These round steel legs with a flat plate provide the proper grip on the seabed. With their large contact surface, the plates prevent the legs from sinking too deeply into the sandy soil.

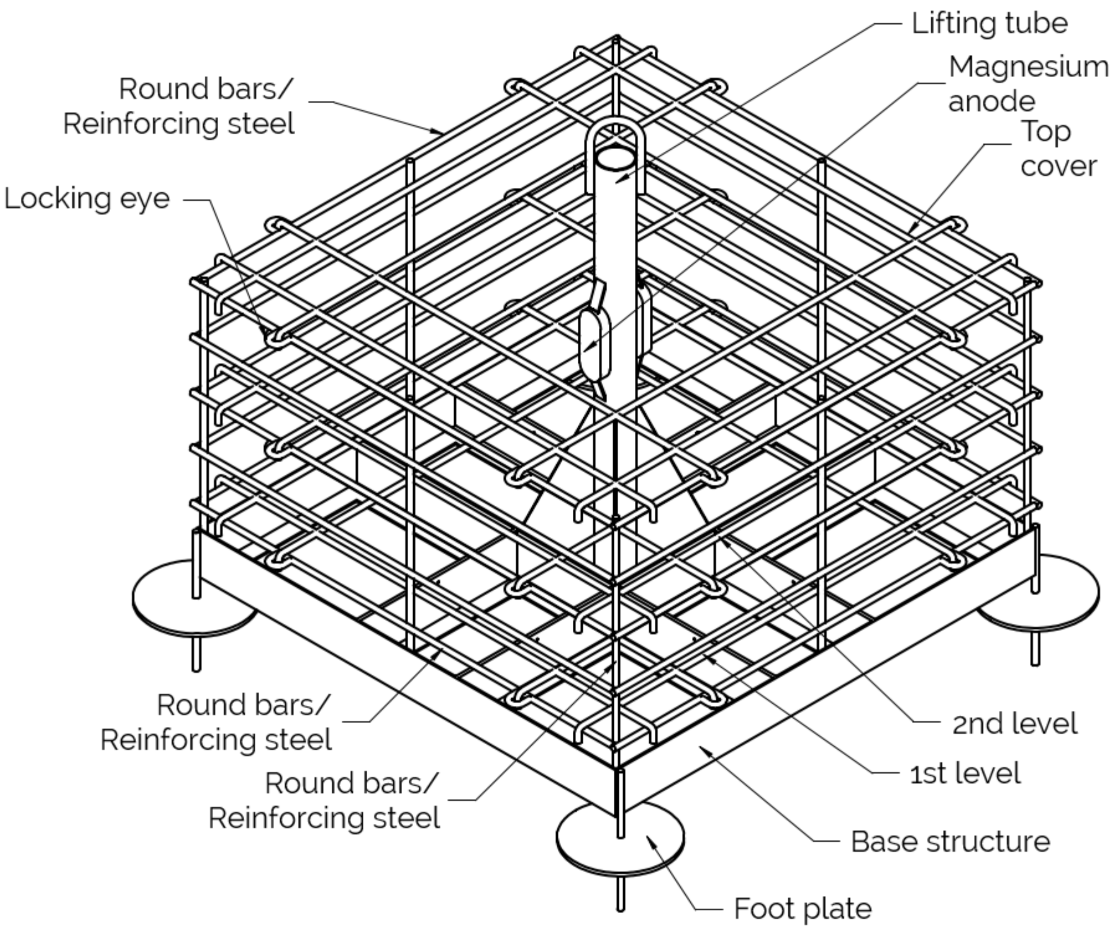

Figure 20: Overview oyster system deployed at German North Sea Pilot

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In addition to its function as a baseplate, the lower part also serves as a container for the ballast concrete weights. This prevents them from slipping and allows them to be mounted easily. The plates are secured with the help of pins that are inserted through the crossbars so that the plates cannot be pushed out.

Figure 21 shows the completely assembled system. Note how the oyster baskets are arranged in the cage. There are four baskets for the oysters on each of the two layers. These are attached to the cross struts of the cage with coated steel wires and additional cable straps. Thanks to the staggered arrangement of the baskets, the door of the individual baskets can be opened easily for filling them with oysters. The doors of the baskets are secured with cotter pins after filling them to prevent unintentional opening. Two sacrificial anodes are attached to the hoisting tube of the system to protect it from excessive corrosion.

Figure 21: Oyster cage ready for deployment

For lifting the cage from the seabed an acoustic release system is attached to the hoisting eye at the tube. The acoustic release system consists of several

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components (Figure 22). The main part is the releaser, which is installed in the acoustic release canister (ARC). Together with orange floaters it will later ensure that this part of the ARC floats to the surface when triggered (Figure 23). The releaser is connected to the oyster system via the release lug, using a chain. This keeps the release system in position under water. In the event of a release, buoyancy bodies are set free and will rise with the releaser. A high-strength rope in the ARC remains connected to the oyster cage. The oyster cage can then be retrieved using this rope (Figure 23). The triggering itself is initiated by an acoustic signal from the deck unit (Figure 22).

Figure 22: Components of the acoustic release system. Left: control/deck unit. Right: releaser

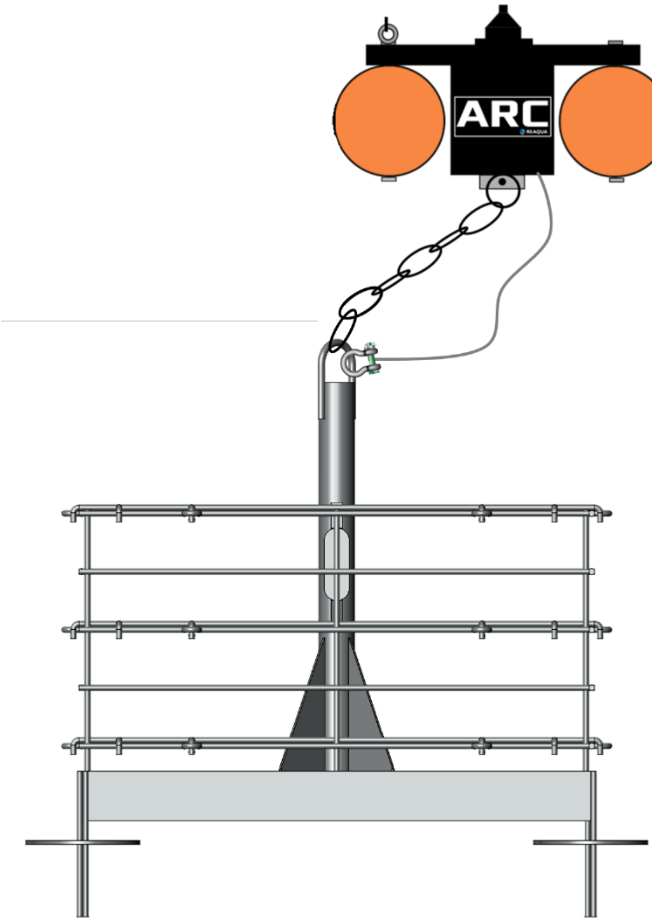

Figure 23: Attachment method of the acoustic release system of the oyster cage

2.3.2 Belgian pilot design

Oyster aquaculture structure attachment to the offshore longlines

In the design phase, the project aimed to develop and test multi-use offshore aquaculture structures integrated within offshore wind farms. Here, we focus on the methods and techniques used to connect various aquaculture structures to the main backbone (longline) which was installed in the offshore wind farm Belwind. The installation involved oyster ladder systems, lantern baskets, ropes with cemented oysters, buoys, and transmitter devices for tracking.

The offshore environment presents specific challenges, such as high wave forces, corrosion, and wear on connection points. Therefore, robust attachment methods and appropriate materials are critical to ensure stability and longevity of the installed structures. All materials were attached by skilled marine technicians who work daily at sea. The methodology of attachments had been used before in a nearshore testing phase within the HORIZON 2020 project UNITED. With the lessons learnt from there, we continued here and chose only the best performing structures and methods.

Materials and methods

General method for connecting structures to the backbone

All structures were attached to the main backbone using durable ropes and specific knotting techniques to ensure security under offshore conditions. The main methods included:

- Primary knot: Mast throw (mastknoop) using an 8 mm nylon rope or Deltaflex rope with diameters of 16 mm or 22 mm, depending on the specific structure and its function.
- Additional safety measure: A secondary safety knot was applied to the section of the rope behind the primary knot to prevent slippage.
- Minimizing slack: To reduce movement caused by wave forces, the connection ropes were kept as short as possible, with minimal space between the structures and the backbone.

For structures with pre-installed metal loops, a timber hitch (timmermansknoop) was used as the primary attachment method, with an extra safety knot added.

2.3.2.1 Oyster ladder systems with SEAPA baskets

Design overview

Two different designs of ladder systems were developed to evaluate various methods of oyster cultivation. Each design was installed in duplicate, resulting in four ladder systems attached to the backbone.

Materials and dimensions

- Rope type: 22 mm braided nylon or Deltaflex rope
- Additional component: Zinc blocks (1000 g each) were attached to all metal structures to prevent corrosion. The zinc blocks, featuring two attachment eyes, were secured using high-quality tie wraps.
- **Design 1** (Figure 24): Stacked baskets in a 1 x 4 arrangement

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Figure 24: Stacked SEAPA-baskets in a 1 x 4 arrangement

Dimensions:

Length: 74 cm

Width: 38 cm

Height: 67 cm

The loop for attachment (Figure 25) is positioned at the center of the width (W = 34 cm). The inner diameter of the loop is 4 cm.

Figure 25: Loop of the frame design

- **Design 2** (Figure 26): Stacked baskets in a 2x2 arrangement

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Figure 26: Frame design to add stacked SEAPA-baskets in a 2 x 2 arrangement

Dimensions:

Length: 75 cm

Width: 68 cm

Height: 33 cm

The loop for attachment is positioned at the center of the width (W = 34 cm). The inner diameter of the loop is 4 cm.

2.3.2.2 A heavy metal cage design was tailor made for direct oyster stocking without baskets

This design (Figure 27) avoids the use of plastic baskets and stocks oysters directly in the metal structure. The weight of the cage reduces swinging and movement of the European flat oysters stocked inside. By limiting movement in the grow-out structures, we anticipated better growth conditions for the oysters. During transport and installation, it became clear that for upscaling, a different design with lighter cages would be required as the cage needed lifting by two people. The skilled marine technicians advised against the heavy weight and suggested using a different material or design for upscaling.

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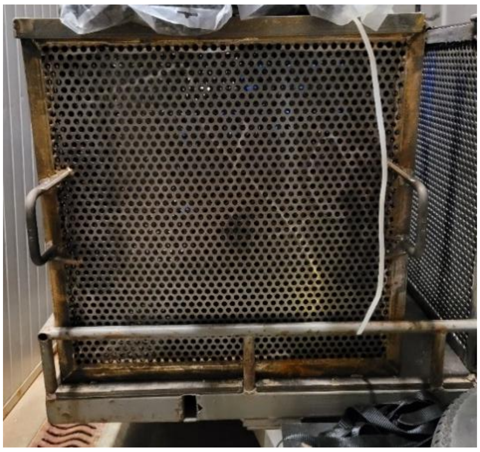
Figure 27: heavy metal cage design

Remark: Special attention was required for the door closing mechanism, as the pin that secures the door might have become loose during offshore operation. Additional tie wraps were used for reinforcement to prevent accidental opening of the doors.

Dimensions:

Length: 66 cm

Width: 65 cm

Height: 46 cm

Four handles are attached for practical handling and lifting. Each handle is positioned from 26 cm to 39 cm along the length, with an inner diameter of 11 cm.

The rope passes through each handle (Figure 28) multiple times (minimum of three, with four to five recommended for extra security).


Figure 28: handle of the heavy metal cage

Attachment method:

For each eye of the structure, a 22 mm rope was looped three times to reduce wear and tear at the attachment point.

The loose ends of the rope were secured to the backbone using a timber hitch.

A secondary safety knot was added behind the timber hitch for extra security.

2.3.2.3 Transmitters ("Pingers")

To facilitate tracking of the four ladder systems and two heavy metal cages, six transmitters were attached to the structures using tie wraps and an additional rope with a protective garden hose around the pinger. Each transmitter operates at a unique frequency, allowing for clear differentiation during tracking operations.

Five units of EMT-01-1 were deployed, with a 1 km range and 48 months battery life, operating ate 5 different frequencies. In addition, one unit EMT-01-2 was deployed, with a range of 3 km and a battery life of 18 months and working at a sixth frequency.

Each pinger was labeled with a corresponding structure number for easy identification. The pingers were attached using high-quality tie wraps and secured with an additional rope to ensure stability under offshore conditions.

2.3.2.4 Buoys attached directly to the longline

Buoys (Figure 29) were connected using 14 mm braided nylon ropes.

Figure 29: example of the buoys connected directly to the backbone

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2.3.2.5 Ropes with cemented oysters

Although the nearshore testing phase showed that the rope system was not ideal due to significant fouling, we continued using the ropes offshore, anticipating less fouling in this environment. The preparation of the oysters on this size of ropes (slightly thicker than those used nearshore) was labor-intensive and required skilled and motivated hands in the last 36 to 12 hours before leaving offshore. A sea mission is always confirmed at the last minute due to weather forecasts, so much of the work needs to be done just before departure. Preparing the ropes earlier would require a safe storage site for the oysters until deployment at sea. Despite the delicate nature of the oysters, careful handling during transport and installation minimized losses.

Twelve ropes with cemented oysters (Figure 30) were installed. Each rope (13 mm Tiptolon braided nylon) was weighted at the lower end and attached to the backbone at the upper end using a mast throw knot (Figure 31).

Figure 30: Ropes with cemented oysters

Figure 31: weights attached to the ropes at the lower end of the ropes

2.3.2.6 Lantern baskets

Six lantern baskets (Ostriga brand) were connected to the backbone. Each lantern consisted of three layers of blue baskets (Figure 32). The connection method followed the same approach as for the ropes with cemented oysters.

Figure 32: blue lantern baskets (Ostriga) with weights connected at the lower end of the rope

Results upon installation

The results upon installation showed successful deployment and stability of all structures in offshore conditions:

- **Oyster ladder systems**: All four ladder systems remained stable throughout the initial deployment period. The zinc blocks attached were to minimize corrosion of metal components.
- **Heavy metal cages**: The direct stocking of oysters in the heavy cages went well, but the handling and installation process revealed that a lighter design is necessary for future scaling. The added tie wraps on the door mechanism were attached to prevent accidental openings. The zinc blocks attached were to minimize corrosion of metal components.
- **Transmitters (Pingers)**: All six transmitters operated correctly and transmitted distinct signals during tracking. The protective garden hose around the pingers ensured that they remained securely attached.
- **Buoys**: The buoys connected directly to the longlines provided sufficient buoyancy and were securely connected to the backbone. The rope connections had proven to be reliable under high wave forces in the nearshore phase and were expected to perform similarly offshore.

- **Ropes with cemented oysters**: Handling needed to be done carefully, ensuring minimal oyster loss was observed during deployment.
- **Lantern baskets**: The lantern baskets remained securely attached during installation, and their three-layer design was to facilitate handling.

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3. Antifouling solutions

3.1 German Pilot(s)

Antifouling in the marine environment refers to the prevention of biofouling, the accumulation of marine organisms such as algae, barnacles, and mussels on submerged surfaces.

Traditionally, biocidal coatings have been the most common antifouling method. However, these coatings release toxic compounds that deter or kill fouling organisms. While biocidal coatings remain effective, we decided against such environmentally unfriendly options.

A more sustainable approach involves foul-release coatings, which prevent organism attachment by creating a smooth, hydrophobic surface. Silicone-based and fluoropolymer coatings are commonly used. However, they are less effective for stationary structures like buoys or offshore platforms and are hence also not suitable for a mainly stationary offshore approach.

For the German pilot cases in the North and Baltic Seas, not all structures required protection from fouling organisms. In the **North Sea,** special attention was given to antifouling measures for the oyster cultivation system. Since oysters readily accumulate toxic compounds in their flesh due to their filtration capacity, a non-toxic solution was paramount. The oyster system needed to stay submerged for extended periods while ensuring sufficient water flow through the baskets, without the risk of oysters absorbing toxins or coatings. After extensive discussions with oyster cultivation experts, **mechanical abrasion** was chosen as the final solution—an easy yet effective way to clean the surfaces of the oyster baskets. A movable ring was applied around the baskets, adjusted to their circumference, allowing it to move freely with changing currents and tides.

The success of this construction will be evaluated when the oyster system is retrieved again in late 2025

In the **Baltic Sea pilot**, protecting the monitoring system—particularly the underwater cameras—from biofouling was a key concern. Although the use of UV light is a well-established antifouling method, also here **mechanical abrasion** was selected as the preferred solution, ensuring consistent lens clarity. The underwater cameras were equipped with **automated wipers** that regularly cleaned the lenses at set intervals. This method proved to be both simple and highly effective, preventing the accumulation of biofouling while maintaining excellent image quality.

3.2 Belgian pilot

Anti-fouling efforts in the oyster cultivation baskets

To combat biofouling on oyster baskets, a novel antifouling design (Figure 33) was developed and tested. Three distinct configurations were employed: control baskets with no fouling prevention, baskets featuring revolving frames that functioned like windshield wipers to scrub the plastic surface, and baskets equipped with revolving ropes that moved across the surface, either preventing fouling organisms from attaching or removing early-stage growth.

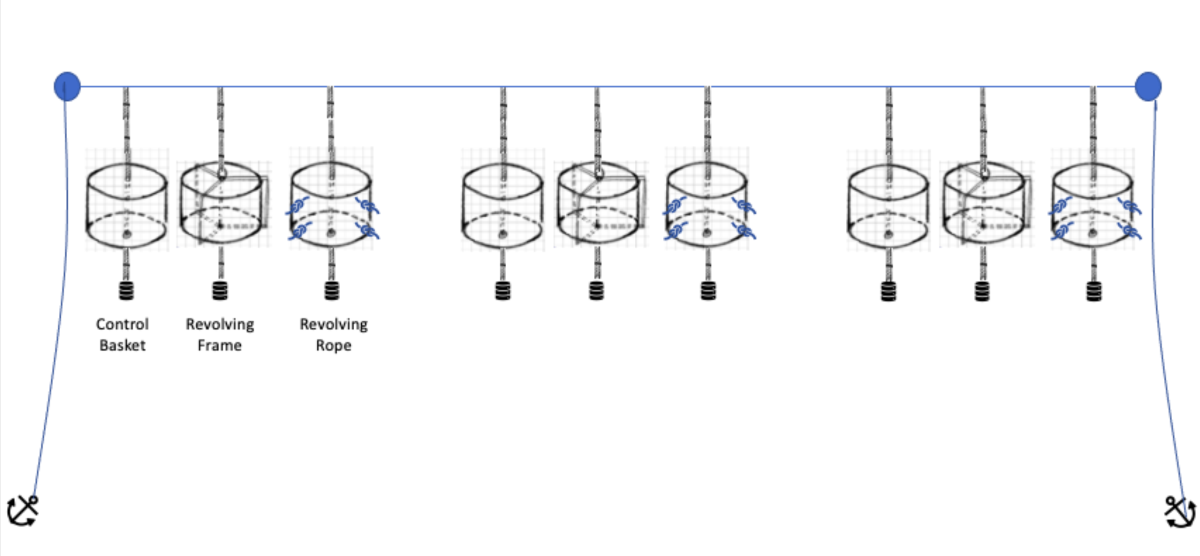

Figure 33: Three distinct configurations were employed as antifouling control: control baskets with no fouling prevention (left), baskets featuring revolving frames (middle), and baskets equipped with revolving ropes (right). This in triplicate.

The initial trial took place in the sheltered harbor of Nieuwpoort, where baskets were positioned beneath a quay. This controlled environment allowed for a one-week trial, confirming the antifouling mechanisms' effectiveness under calm conditions. However, this was only a preliminary test to assess whether the system could function in real-world settings. It was not designed to provide statistically significant data on fouling differences but rather to evaluate the system's robustness in a calm environment.

Building on these promising results, the baskets were moved to the Bantry Marine Research Station (BMRS) in Ireland for further testing in open, high-energy coastal conditions. The baskets were suspended on longlines, simulating real offshore cultivation. Unfortunately, due to severe storm conditions, all baskets were lost during the trial.

This setback underscored a critical insight: while the antifouling designs performed well in sheltered nearshore environments, they were not resilient enough to withstand the challenges of offshore conditions. As a result, the use of this specific cultivation structure has been discontinued. Nevertheless, the antifouling system demonstrated its functionality during the nearshore trial, showing promise for future refinement in calmer environments.

3.3 Danish Pilots

The Danish pilots intended to cultivate mussels and seaweeds. Mussels were recruited from wild spat, and are themselves considered a biofouling organism for other purposes. Timing of spat collector deployment is a general practice to avoid other fouling organisms, such as barnacles and tunicates. Mussel spat settlement timing was not known prior to deployment, so an optimal deployment strategy to avoid other fouling organisms was not executed. The seaweed cultivation period was expected to avoid major fouling settlement periods, though this is not strictly an anti-fouling strategy. Monitoring instruments were wrapped in copper and equipped with wipers.

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4. Optimizing growth potential is needed

In this chapter the need for growth optimization is described per pilot. Since the pilots have different design stages this is not relevant to all.

4.1 German cases:

4.1.1 Optimizing Offshore Sugar Kelp Cultivation: Comparing Pre-Seeded Twine and Direct-Seeding Nets

Offshore sugar kelp cultivation can be optimized by selecting the most suitable seeding method. Two common approaches are the use of pre-seeded twine and direct-seeding of the nets, each with distinct advantages and challenges.

Pre-seeded twine is particularly effective for rope-based cultivation. Since the seedlings are pre-cultivated in a nursery, they have a head start in growth and can firmly attach to the ropes, reducing the risk of being washed away by strong currents, waves, or tidal action. However, this method is not well-suited for net-based cultivation, as handling and applying twine on large net structures is impractical.

Direct-seeding of nets, on the other hand, offer an efficient approach for large-scale deployment, particularly when specialized machines are used to spread seedlings evenly. This method allows for rapid seeding over extensive areas, making it attractive for net-based systems. However, the seedlings are more vulnerable to being washed away due to their lack of pre-cultivation. Additionally, if seeding is done manually, the distribution of seedlings can be uneven, leading to patchy growth.

Choosing between these methods depends on the specific cultivation setup and environmental conditions. For rope-based cultivation, pre-seeded twine offers greater seedling stability and growth success, while direct-seeding nets provide a scalable and efficient option for large net-based systems, albeit with higher risk of seedling loss

4.1.2 Optimizing Offshore Mussel Cultivation Techniques

Tests of **different net structures** for offshore mussel cultivation revealed significant variations in performance. The goal was to identify an efficient system for both mussel-spat settlement and grow-out in a single step, without the need for resocking or thinning out mussels. However, the results showed that not all net structures performed equally well.

One of the tested structures, the Christmas tree / fuzzy rope—known for its effectiveness in mussel spat collection—did not meet expectations. Despite its promising design, it failed to yield satisfactory results under offshore conditions.

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This highlights the need for **site-specific adaptations** and further refinement of net structures to ensure both reliable spat settlement and optimal mussel growth.

Since the tested system was designed to avoid labor-intensive resocking, mussels remained at their original densities throughout the grow-out phase. While this approach reduces handling efforts, it can also lead to competition for space and nutrients, potentially limiting growth rates and final yields. Future optimization efforts should focus on identifying net structures that provide both high spat retention and stable growth conditions, while also considering whether a limited degree of thinning might improve overall productivity.

4.1.3 Optimizing Offshore Oyster Cultivation Techniques

Offshore oyster farming presents unique challenges and opportunities, with **submerged cultivation systems** offering key advantages. Unlike surface-based structures, submerged oyster baskets do not interfere with shipping routes or other surface activities, making them a preferred choice for offshore environments. However, optimizing these systems requires careful consideration of basket design, mesh size, stocking density, and oyster size at deployment.

One critical factor is the selection of an appropriate basket mesh size. If the mesh openings are too large, smaller oysters are risked to be washed out by strong currents and wave action. Therefore, oysters must reach a certain minimum size before transferring to the offshore grow-out system to ensure retention. Additionally, the durability and hydrodynamic performance of the baskets play a crucial role in withstanding offshore conditions, including high-energy waves and shifting water currents.

Another limitation is stocking density. Since basket size is fixed, the number of oysters per unit is constrained, meaning that growth efficiency must be maximized within these spatial limits. Overcrowding can lead to competition for food and reduced growth rates, while understocking may not fully utilize the system's capacity. Regular monitoring and adjustments to stocking densities can help optimize yield.

Further improvements in offshore oyster farming could involve innovative basket designs that enhance water flow while preventing sediment buildup, as well as automated systems for monitoring growth and environmental conditions. Advancements in selective breeding for faster-growing, more resilient oysters could also support higher productivity in offshore conditions.

4.2 Danish cases

4.2.1 Seaweed

To enhance seaweed production at the Anholt pilot site, various methods are being explored. Firstly, different species are being tested to determine their specific growth potential. Secondly, different configurations, as outlined in section 2.1.1, are being evaluated to understand the impact of depth on growth and the practical aspects of deploying seaweed vertically versus horizontally. Lastly, the feasibility of improving growth through multi-annual cultivation and/or summer production in deeper, cooler waters is being investigated. For all trials, the Danish pilot used lines or nets that were seeded in the hatchery and nursed for 6-12 weeks before deployment at the OWF. The method of direct seeding where a nursing phase can be avoided, was not chosen for this project as the method has not shown very good results in Danish waters. Instead to get a first idea of the growth potential at the offshore wind farm, it was chosen to go with the method best known to work in the local environment.

4.2.2 Mussels

Different spat collectors, as well as nets, were deployed to compare spat collection and retention potential. A preliminary uncertainty was the presence of sufficient larval mussels to settle in the pilot areas, and primary settlement periods (spring or autumn). Differences in spat collectors included ballast configuration (weighted along the collector length vs. weighted at the bottom of the continuous loop) and collector surface area; which implies cost differences, associated harvest gear, and suitability for a high-energy environment between collector types. In conjunction with environmental and physical monitoring, mussel retention and growth will be monitored to estimate optimal continuous loop dimensions and depth specifications.

4.3 Dutch pilot

The Semi-submersible Mussel Farm is deployed for the first time in the ULTFARMS project. Thus, growth data with the present line configuration are needed before optimisation can take place.

4.4 Belgian Pilot

The work/plan for optimization of growth potential for the Belgian pilot is reported in WP4, where the effective implementation in the pilot is described.

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5. Seaweed nursery

The need and extent of a seaweed nursery depends on the type of macroalgae chosen, its cultivation strategy, its intended site of installation (nearshore vs. offshore) and method of implementation (direct vs. twine seeding).

For both established methodologies, few production costs are reported. For twine seeding, the cost range for each meter lies between $0.12 - $1.38 and are dependent on the production method, species and geography (Coleman et al., 2022), as well as labour and energy costs. There are few reports on the associated nursery costs of direct seeding, however, a reduction of 13-23% for *S. latissima* production has been observed (Bak et al., 2019). Nevertheless, multiple factors influence the final costs associated with each methodology and currently, require case specific decision making.

German pilot: Method selection and culture preparation
For large scale offshore installations, the project partner Hortimare delivered high quality seedling material, as timely delivery and quality assurance is key for a successful deployment in any cultivation nearshore or offshore. Common bottlenecks in seaweed aquaculture, is the seasonal variation in mature tissue within wild populations, which serves as a basis for the following hatchery production of seeding material. To optimize this, increased sampling efforts have been conducted, while also leveraging novel induction techniques. Those include the artificial induction of vegetative tissue of *S. latissima*, for the generation of new cultures as described recently (Boderskov et al., 2021).
The nearshore installations in Kiel Bay, include both methodologies direct and twine seeding. For such small-scale installations, twine seeding was prepared in house, from local seaweed populations, at the German pilot nearshore sites, while seeding material for direct seeding was supplied by Hortimare. This aims at investigating ideal seaweed preparation and installations settings (D4.1, RP1), which pivoted in a larger installation, comparing direct and twine seeding of *Saccharina latissima* in Kiel Bay (ULTFARMS news, February 2025). The partial harvest indicated similar growth rates in weekly length gain for twine (0.86 cm) and direct seeding (0.74 cm), however, overall biomass harvest implies greater yields for the twine seeding, aligning with the literature found on *S. latissima*. Further installations and harvests are scheduled, which will enable more insights.

In the **Belgian Pilot** seeding was tested using the optimized 2-step direct seeding approach, where no nursery was needed.

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6. Connections with other ULTFARMS work packages/tasks

This deliverable is linked to D3.1, D3.2, D3.3, D4.1, D4.2 and D10.3. Following paragraphs elaborate further on these connections giving examples per pilot and concludes with additional Cross-work package and overall pilot connections.

The optimized cultivation setups found for seaweed and mussel systems in both **German pilots** (North Sea and Baltic Sea) are highly specialized in their task. In that manner, the improved attachment methods (anchoring and mooring structures) have played a vital role in that process. For the North Sea pilot, the anchor moorings have been optimized to withstand harsh winter storms, while for the Baltic pilot, novel anchoring techniques have been developed. Both techniques were designed (D3.1) and throughout tested in nearshore settings (D4.1). After fine-tuning, which resulted from iterative design and testing loops, deployment was successful and the design and attachment methods proven suitable for their specific purpose (D4.2). The cost estimates and feasibility will be focused in the subsequent tasks of economic evaluation (Wp5) and feeds into the general roadmap of ULTFARMS (WP10). A risk assessment and legal requirements was conducted and reported (D3.2, D4.2, D10.3,). Technical and biological considerations have been gained and reported (D10.3), which include system design, choice of species and location as well as environmental considerations. All these insights will feed into the overall ULTFARMS roadmap, which formulates considerations of most tasks and focusses on scaling opportunities.

The **Dutch pilot** contributed to D3.5 (Feasibility study for implementation of power supply at sea), D3.1 (Co-design of production-related activities), D3.4 (Sensor technology design) and D3.2 (Design, numerical modelling of a submersible longline). The SMF is deployed in WP4. The mussels produced will be submitted to a taste test in WP5. In addition, the performance of the system, the mussels and associated biodiversity will be monitored in WP6. The potential development of a natural reef underneath the farm is monitored in WP7. Installation of reef promoting structures was not carried out in the Borssele windfarm due to permit restrictions. That task was moved to a near-shore location.

The **Belgian pilot**, located in the Belwind Offshore Wind Farm, is a key testbed for seaweed and oyster mariculture. Designs reported in D3.3—particularly the submersible seaweed cultivation structures and the diverse oyster grow-out systems—were developed and iteratively refined in WP3, based on earlier findings from the UNITED project. These systems were first tested nearshore and later deployed offshore. Their performance under North Sea conditions is monitored and evaluated in WP4. The offshore implementation links closely with WP4 Task 4.2 (Offshore implementation and monitoring), where the performance of the longlines, mooring systems, and cultivation substrates are assessed under real-world marine conditions. The activities related to the development of the submersible seaweed aquaculture in the Belgian Pilot have been conducted within the scope of Task 3.2 (T3.2) and reported in deliverable 3.2 (D3.2). These activities, which are presented in detail in D3.2, are as follows:

- Numerical analysis of the first design iteration
- Physical experimental modelling of submersible beam and seaweed net
- Pilot scale deployment of submersible seaweed aquaculture at BMRS
- Numerical analysis of the submersible seaweed aquaculture at BMRS

In addition to the above, a numerical analysis will be conducted to extrapolate the results from the BMRS test to determine the mooring requirements suitable for the Belwind site conditions. This will be reported in D3.5 when the final design of the submersible seaweed longline in the Belgian Pilot is reported.

Results of nearshore testing are reported in D4.1.

The Belgian pilot also contributes significantly to **WP6** through environmental monitoring of both seaweed and oyster deployments, including impacts on local biodiversity and system resilience under high-energy wave conditions. The oyster ladder systems and restoration structures explored in WP3 (D3.3) are part of a broader nature-inclusive strategy aligned with **WP7**, though installation of reef-enhancing elements had to be redirected due to permit limitations. Regulatory feedback and permitting experiences gained through these activities are fed into **WP9**, supporting better understanding of legal bottlenecks and spatial planning challenges in Belgian waters.

Economic implications, including material costs, installation logistics, and system maintenance, are analyzed in **WP5**, which will also assess the market potential of seaweed and oysters produced under these conditions. Biological and technical results from the pilot feed into **WP10**, where they contribute to ULTFARMS' roadmap for scalable offshore LTA development across Europe.

Additional Cross-work package and overall pilot connections

- **WP1 (Coordination and Management):** All pilot activities, technical developments, and cross-WP interactions are coordinated centrally under WP1 to ensure coherence, progress tracking, and milestone delivery.
- **WP2 (Stakeholder Co-Development):** The development of the mariculture structures involved stakeholder engagement in co-design sessions, particularly for site-specific needs, industry relevance, and regulatory feasibility. These consultations helped shape technical priorities in WP3.
- **WP6 (Environmental Monitoring):** All pilot designs in D3.3 are evaluated for their environmental footprint and interactions with local ecosystems. Standardized monitoring protocols across pilots enable comparative evaluation and help validate system sustainability.

- **WP7 (Nature-Inclusive Design):** While WP3 focuses on cultivation design, WP7 evaluates how structural features might be adapted or enhanced to provide ecosystem services such as habitat creation or reef effects.
- **WP8 (Social and Policy Dimensions):** Technical feasibility also interacts with social acceptability and local policy frameworks. Feedback from WP8 helps shape pilot designs in a way that considers local communities, perceptions, and policy frameworks.
- **WP9 (Legal and Governance):** The deployment and permitting experience from D3.3 feeds directly into regulatory mapping, bottleneck identification, and streamlined procedures for LTA system approval.
- **WP10 (Roadmap and Replication):** All technical insights, challenges, and design iterations documented in D3.3 are foundational to the ULTFARMS roadmap, which synthesizes knowledge from all WPs and proposes pathways for upscaling sustainable offshore mariculture across Europe.

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7. Conclusions

German pilots:

The German pilot projects are located in both the Baltic Sea and the North Sea. In the **Baltic Sea**, the focus is on novel **multi-purpose** cultivation systems with anchoring techniques applicable for **attachment to monopile structures**. The **system is adjustable** to specific needs—namely, **algae cultivation** and **nature-inclusive design** approaches. This relatively **small but modular system** is designed for easy installation without compromising the stability of existing monopile structures.

In the **North Sea**, larger and more **robust net systems** were designed and deployed for the cultivation of **blue mussels and algae**. In addition, a **submerged European oyster cultivation system** was developed, allowing it to be removed from harsh surface conditions.

The use of **non-toxic, mechanical antifouling** solutions was a priority in all applications, including the cleaning of camera systems and keeping oyster baskets free of fouling organisms.

To **optimize growth potential**, different approaches were selected for different cultivated organisms. **For algae, two seeding methods** were tested—direct seeding and twine-based seeding. **For blue mussel cultivation, different substrate types** were tested, showing potential for future optimization. Finally, the use of a **bottom cultivation system for European oysters** demonstrated the benefits of removing the system from harsh surface conditions, promoting better growth in a more stable environment.

Danish pilot:

The Danish pilot projects are still in progress, making it premature to draw conclusions about the growth performance and production potential of the tested species.

However, in terms of farm design, the activities so far have demonstrated that adapting a longline production system to offshore conditions is feasible, albeit with higher costs compared to nearshore operations.

As for the tube-and-net system, it is too early to make any conclusions since trials are still underway. The tube-net system in offshore conditions requires increased tube wall thickness relative to standard dimensions used in near- or inshore operations.

Operational challenges have been experienced with vessel compatibility with the physical conditions, ability to work with the farm structures, and limited availability. These limitations of vessel availability reduce the ability to maintain the farm, which increases risk to farming viability. Deployment modifications were implemented to use standard iron anchors and chain moorings rather than screw anchors due to a lack of suitable vessel availability. Subsequently, lessons learned in farm implementation have been largely related to operational considerations.

Dutch pilot:

The Dutch pilot experienced some technical difficulties in installing the longlines due to the inexperience of the boat crew. In addition, the lines broke after 10 months due to unexplained reasons. In April the longlines and continuous loop droppers will be installed.

Belgian pilot :

Evaluation and conclusions from the Belgian pilot oyster cultivation systems in offshore wind farms

The pilot installation of aquaculture structures in the Belwind offshore wind farm provided a valuable evaluation of the robustness and practicality of the systems during transport, on land, and onboard the vessel until installation. While this trial focused on assessing the structural integrity and logistical feasibility of the systems in these stages, the evaluation of their performance under harsh offshore conditions will be addressed separately in another deliverable within WP4 and in the Belgian pilot lessons learned deliverable.

The antifouling mechanisms tested in nearshore environments showed potential, but the inability to withstand challenging offshore conditions highlighted the need for further refinement in design and material resilience. This reinforces the importance of ensuring that systems which perform well in sheltered environments are sufficiently robust for dynamic offshore conditions, where additional durability and weather-resistant materials are essential.

Regarding oyster cultivation, the attachment methods for connecting various aquaculture structures to the backbone of the longlines demonstrated their reliability in securing the systems during transport and installation. The connection methodologies, including durable knotting techniques and safety knots, proved effective under the logistical stresses of deployment. However, the heavy weight of certain structures, such as the metal cages, presented challenges in handling and scaling for larger operations, suggesting that lighter designs would be more suitable for future deployments.

Overall, while the systems were successfully deployed and secured, the evaluation in this phase primarily focused on their robustness during transport and installation. The full assessment of their long-term performance under offshore conditions will be provided in future deliverables. The insights gained from this pilot installation will be instrumental in refining the design and operational strategies for aquaculture systems integrated within offshore wind farms, with a focus on creating more resilient, efficient, and sustainable solutions for such challenging environments.

Evaluation and conclusions from the Belgian pilot seaweed cultivation systems in exposed environment

The seaweed cultivation system was successfully deployed and secured, the evaluation in this phase focused on their robustness during installation and the performance during storms. The insights gained from this installation will be instrumental in refining the design and operational strategies for submersible aquaculture systems in offshore environments.

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