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DELIVERABLE 2.6

TECHNICAL REPORT ON DESIGN PROCEDURE LIMITATIONS AND IMPROVEMENTS

Work Package 2

Technology

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Abstract	Task 2.6 of the UNITED project is summarized in the report, which outlines the technological specifications for each part of multi-use offshore platforms. Within the Multi-use and/or Co-Location platforms (MUCL) paradigm, it identifies areas for design method enhancements by taking stakeholder needs into account. The report clarifies constraints and opportunities by utilizing technical data on environmental

	elements, geographical needs, design structural lifetime, and other topics. Additionally, synergies between MUOP components are explored. The findings highlight the need for industry-wide cooperation and ongoing improvement, and they support global synthesis (WP1) and future MUCL programs.
Keywords	MUCL, limitations, risks, benefits, pilot, procedure, design, improvements
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ACRONYMS

AI	Artificial Intelligence
AIS	Automatic identification system
BPNS	Belgian part of the North Sea
CAPEX	Capital expenditure
CPOD	Continuous porpoise detectors
D	Deliverable
DSS	Decision support system
GMDSS	Global Maritime Distress and Safety System
HOFOR	Copenhagen local energy and water supply
Hs	Significant wave height
HSSE	Health Safety Security and Environment
ISO	International Organization for Standardization
MU	Multi-use
MUCL	Multi-Use platforms and/or Co-Location platforms
MUOP	Multi-use offshore platform
PLB	Personal Locating Beacons
RAMS	Risk Assessment and Method Statement
ROV	Remotely operated vehicle
SOLAS	The International Convention for the Safety of Life at Sea
SOS system	Safe Offshore Operations System
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Sea-farers
TRL	Technology readiness level
WP	Work package

EXECUTIVE SUMMARY

The project, dedicated to advancing multi-use concepts in marine spaces, operates across the North Sea, Baltic Sea, and Mediterranean Sea, focusing on key aspects such as technology, regulatory frameworks, economy, social considerations, and environmental impact. Using five pilot locations that each investigate the integration of various maritime activities, the project aims to improve technological readiness levels (TRL) and encourage stakeholder collaboration.

The report specifically zooms into Work Package 2 (WP2) - Technology, addressing the technological requirements essential for establishing feasible multi-use production sites. Building upon the insights from WP1, it aims to enhance observational and automated networks within existing pilots.

Task 2.6 of the report identifies technological requirements for each component in the multi-use offshore platform, considering the specific needs of stakeholders. By delving into technical information on environmental parameters, spatial requirements, design structural lifetime, and more, the report offers a comprehensive overview. It not only highlights the limitations of existing design procedures but also provides insights into potential improvements. Furthermore, the report explores how the combination of different elements in the multi-use platform yields synergistic benefits. Examining benefits, risks, limitations, and synergies in different marine environments, the analysis offers a nuanced understanding.

In the German Pilot, the mutual interaction between mussel and algae systems enhances nutrient cycling, but logistical and regulatory challenges drive innovation. The Dutch Pilot strategically uses environmental parameters yet faces uncertainties and limitations in data collection. The Belgian Pilot optimizes crew vessel use and achieves operational efficiency, dealing with challenges in extreme weather and diving restrictions.

The Danish Pilot seamlessly integrates tourism with offshore wind energy, emphasizing flexibility but facing weather-dependent challenges. The Greek Pilot enhances aquaculture and diving through real-time monitoring yet contends with weather-dependent operations and logistical challenges.

This comprehensive view contributes to the ongoing development of multi-use offshore platforms, fostering collaboration and elevating technology readiness levels (TRL). The findings directly impact global synthesis efforts and shape the roadmap for efficient and effective multi-use offshore platforms.

The findings presented in this report play a crucial role in informing the development of future Multi-Use Combined Layout (MUCL) projects. By shedding light on necessary improvements to design procedures, assessing potential risks, and exploring the possibilities of combining different elements for synergistic benefits, the report contributes directly to the global synthesis of WP1. Additionally, it aids in the formulation of roadmap designs in Task 5 of WP1, enabling the implementation of efficient and effective multi-use offshore platforms.

1. INTRODUCTION

1.1. BACKGROUND ON THE MULTI-USE OFFSHORE PLATFORM (MUOP)

UNITED aims to facilitate the widespread implementation of multi-use of marine spaces through the development of pilots in marine environments, focusing on five key aspects: technology, regulatory framework, economy, social considerations, and environmental impact. The project intends to achieve optimal multi-use concepts and co-location activities by closely collaborating with local stakeholders and industrial actors. It seeks to enhance the technology readiness level (TRL) from TRL5 to TRL 7+ by addressing challenges and providing solutions in all five pillars, thereby promoting economic benefits, particularly in renewable energy, aquaculture, and tourism sectors.

Drawing on successful designs and overcoming regulatory and technological barriers identified in previous projects related to Multi-Use platforms and/or Co-Location at platforms (MUCL), UNITED aims to further develop and re-fine these concepts across five pilot sites in the North Sea, Baltic Sea, and Mediterranean Sea. This collaborative effort involves industrial actors and leverages knowledge, technologies, and facilities to explore multi-use plat-forms and the co-location of various marine activities. The five pilots represent diverse dynamic conditions in different regional seas and provide insights into the advantages, challenges, and risks associated with different combinations of marine activities. UNITED specifically focuses on the economic benefits derived from combining renewable energy (wind and solar), aquaculture, bio-resources, environmental restoration (such as oyster bed restoration), maritime transport, and tourism services within the same marine space. The project achieves this by developing offshore monitoring solutions tailored to multi-use operations, optimizing offshore operations to re-duce costs and space requirements, and enhancing previously developed business models to mitigate risks for operators and investors.

Work package 2 (WP2) – Technology – addresses the technological requirements necessary to establish feasible multi-use production sites, building upon the findings from WP1. The project aims to enhance observational and automated networks within the existing pilots, enabling an integrated system that collects, processes, and stores information from a range of sensors. This integration improves operational aspects of multi-use platforms and optimizes the utilization of marine space.

For MUCL, there are specific technological challenges related to the co-location and co-use of maritime space. These challenges include the need for specialized monitoring equipment with multi-functionality, capable of cap-turing various variables required to evaluate and manage multiple co-located uses that are not traditionally inte-grated. Additionally, the equipment needs to be adapted to the specific conditions of offshore locations, including limited accessibility. This report provides insights into the monitoring, mooring, docking, and management sys-tems of the marine platforms, highlighting the optimizations necessary for conducting MUCL activities within the UNITED project. The report is developed in close collaboration with each pilot, ensuring a precise and effective combination of platform requirements, special considerations, available technologies, and infrastructure imple-mented at the pilot sites.

1.2. PURPOSE OF THE REPORT

The report will serve as a comprehensive overview of the Task 2.6 at hand, which involves identifying the techno-logical requirements for each component in the multi-use offshore platform. It will take into account the specific requirements of the stakeholders and examine areas where design procedures need improvement to be accepted as part of the MUCL concept. The objectives of Task 2.6 are outlined, emphasizing the identification of technolog-ical requirements and enhancements to design procedures for multi-use offshore platforms. The analysis provides a detailed examination of each MUCL element, discussing challenges, limitations, and possibilities for improve-ments. This includes considerations for environmental impacts, structural requirements, and logistical aspects.

The report will draw upon the findings regarding the technical information for each MUCL element highlighting the design procedures limitations and possibilities for improvements as well as highlighting the manners through which the combination of elements yield synergies. According to Christensen et al., in offshore wind, a major portion of the cost is attributed to capital expenditure (CAPEX), accounting for around 80% of the cost of energy, while operating expenditures represent only 20%. On the other hand, in aquaculture, operating expenditures con-stitute a significantly higher percentage (70-80%). Despite these differences, both industries share the utilization of ocean space, although the spatial extent of a fish farm is considerably smaller compared to an offshore wind farm. Furthermore, the operational nature of the two industries varies significantly.

Each MUCL component's critical aspects are meticulously addressed, encompassing environmental parameters (wind speed, wave action, currents, temperature, salinity, and oxygen content), spatial requirements, design structural lifetime, and design loads. The report further explores logistical planning, accessibility challenges, and maintenance operations, drawing practical lessons from pilot implementations and noting similarities and differences in various phases. Positioning itself as a strategic guide, the document concludes by offering actionable recommendations for future MUCL initiatives. It highlights the importance of refining design procedures, mitigating risks, and capitalizing on synergies among different elements.

The report establishes a connection with relevant deliverables (UNITED D1.1 (2020), D2.5 (2023), D6.1 (2021), D6.2 (2023), D7.4 (2022), D7.5 (2023)) across the entire project, enhancing reader engagement and providing a roadmap for accessing more detailed information. The acknowledgment of the experimental nature of technical innovations underscores the importance of referring to these deliverables and potential publications for in-depth insights and design plans. The deliverables can be found on the UNITED website in the publications tab.

In conclusion, this comprehensive overview serves as a strategic guide for future MUCL initiatives, offering actionable recommendations for refining design procedures, assessing and mitigating risks, and strategically capitalizing on synergies among different elements. This document not only contributes significantly to the goals of WP1 but also serves as a bridge between different work packages. By offering actionable recommendations, assessing risks, and strategically capitalizing on synergies among various elements, the insights provided in this report pave the way for the development of efficient and effective multi-use offshore platforms.

2. GERMAN PILOT

The German pilot is situated 80 kilometres north of the island Helgoland in a highly exposed marine environment within the North Sea. The purpose of erecting the "FINO 3" (Figure 1) sensor tower, standing at a height of 120 meters with a working platform positioned 22 meters above sea level, is to facilitate research endeavours aimed at facilitating the establishment of wind farms. It is now open to public. Near to the DanTysk wind park, which harnesses the power of 80 wind turbines to generate 288 MW of electricity (source: www.dantysk.de), an aquaculture system has been established within the safety zone surrounding FINO 3, spanning a radius of 500 meters. The aquaculture system consists of two parallel 40 m long lines. One of these lines is dedicated to cultivating algae directly at the sea surface, allowing for maximal exposure to sunlight, thereby promoting optimal algae growth. The second line is designed for submersible mussel growth. To ensure the stability of the system the nets for mussel growth hanging from the long line, are at a dept from 7 to 12 meters, effectively removing the system from the wave zone. In between the two long line systems a "lander" with monitoring equipment was deployed.

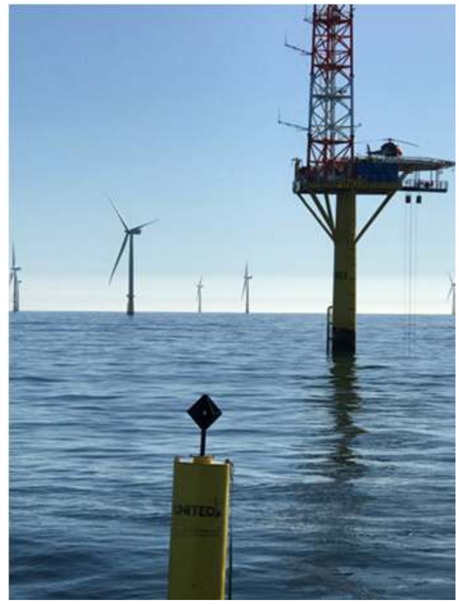

Figure 1: FINO3 platform

2.1. Technical information

Environmental parameters

At the near shore site of the German Pilot, different antifouling approaches were tested to identify the most suitable for sensor protection. Special attention was given to biocide-free, non-toxic antifouling techniques to cater for the strict regulations in human food production to prevent contamination of mussels and algae with potentially harmful substances. The tests have shown three very successful protection strategies. Coating of surfaces with A-BIO, a non-toxic, commercially available anti-fouling agent, UC-C radiation and regular mechanical cleaning by wipers.

The multi-parameter probes (CTD, turbidity, O2, and PAR-light) have been equipped with a UV-C lamp. The assembly of the individual sensor probes in the housing did not allow mechanical wipers for anti-fouling protection or the usage of a coating.

The sensor equipment for the Lander and the Lander and winder unit itself has undergone testing to ensure functionality. 4HJena has relied on their know-how and feedback from previous installations with similar or identical equipment. Functional tests of the individual sensors and a final test of the overall function were conducted in the laboratory and workshop of 4HJena.

The NO3 sensor: chosen for its widespread use, was equipped with a wiper for biofouling protection. In the laboratory, interval settings, battery performance, and logging capacity were thoroughly tested.

The Hobo sensors underwent functionality testing and setup in the 4HJena lab. Since similar sensors were already in regular use at KMF, there was no need for a specific test at the nearshore site.

The CTD sensor: which includes light and O2 measurement capabilities, was chosen as a standard equipment from AML Oceanographic for global hydrological data monitoring. Its operation and communication were verified in the 4HJena lab.

ADCP-sensor: The Nortek Signature 500 is standard equipment that is known to function well and widely used in marine traffic and environmental monitoring. Operation and communication were verified in the lab.

HydroC CO2: Is 4HJena's standard sensor for CO2 measurement, for which they have all the required installation and operation know-how. Operation and communication were verified in the lab.

The AquaREAL buoy is equipped with four sensors measuring the following parameters (AquaTROLL):

• Water temperature

• Dissolved oxygen

• pH

• Turbidity

Salinity/conductivity is not included, due to the limit of four sensors per system, as well as this parameter is considered relatively 'constant' with minimal impact on mussel/seaweed Every 20 minutes, data is sent directly from the measurement buoy to a Gateway (LoRaWAN) installed at the FINO3 tower and from there, transferred into 'cloud storage' (requires permanent internet connection). Due to the considerable movement of the longline, the measurement buoy is not connected to the lander.

General parameters such as pH, temperature, salinity, torpidity and wave height are important for growth in the systems such as salinity and temperature or turbidity, others also important for the physical stability of the system itself (anchoring, stress on ropes and lines).

Some specific parameters:

- Temperature: If it is too high or too low, then growth is prevented.
- Turbidity: is an important proxy for food content (algae and crustations) for mussel and also an important proxy to assess the penetration depth of light determining the growth limit of algae.
- NO3: is important as nutrient for algae, but also important as measurement of excreted N by mussels and used for assessment of environmental impact or the system.

The main problem is that the far offshore location, 80 km off the coast, is hard to reach and very expensive. Usage of the nearshore site is hence crucial. Limitations exist as the water depth and salinity is different in the nearshore site. Hence only material and sensor testing of different components is possible and a scaled model of the system could be tested and not the real system. Hence it has to be relied on knowledge and experiences form the partners.

Spatial requirements

The spatial requirements for each MUCL element were taken into consideration during the design process. Due to the limitations posed by the worldwide pandemic and closed borders, a combination of drag anchors and clump weights was chosen for the German Pilot instead of screw anchors. This decision was made to avoid relying on special equipment and external subcontractors from abroad for installation. The risk associated with travel restrictions, last-minute cancellations, and unforeseen incidents was deemed too high. Additionally, the mussel and seaweed designs were based on previously tested systems adapted to the conditions of the German Pilot location, incorporating clump weights and/or drag anchor mooring solutions. Using screw anchors would have required costly modifications to these existing systems.

The limitations of the current design procedures were primarily related to the challenges posed by the worldwide pandemic and closed borders. These limitations included the inability to plan for installation involving special equipment and external subcontractors from abroad. The increased risks associated with travel restrictions, unforeseen incidents, and last-minute cancellations further constrained the design process.

The design structural lifetime was taken into consideration during the design process. The aim was to ensure that the structures would be durable and capable of withstanding the expected operational conditions for an extended period.

The design lifetime for the structures was determined based on various factors, including the expected operational conditions and the desired longevity of the aquaculture systems. The goal was to establish a design lifetime that would accommodate the growth period of both the mussels and seaweed, while considering factors such as extreme growth and biofouling.

The determined structural lifetime influenced the design procedures by necessitating the inclusion of sufficient buoyancy and reserves for extreme growth and biofouling. It was crucial to ensure that the systems would remain afloat throughout the entire growth period, even under challenging conditions. The use of spar buoys, known for their slow reaction to wave movements, was incorporated to mitigate the turbulent effects of wave motion on the systems.

The limitations of the current design procedures were primarily related to the absence of specific standards for offshore mussel and seaweed cultivation systems. To address this, verification by an independent company was commissioned to assess system dynamics, evaluate the risk of equipment failure, and revise loads and movements based on mooring and fish aquaculture standards. The lack of standardized guidelines for these specific systems posed a limitation in the design process.

Logistics planning

Logistics planning for the algae and mussel system encompassed a comprehensive set of considerations, addressing various aspects of the project's execution. In particular, the team responsible for these logistics had to adhere to specific prerequisites, notably acquiring specialized training for offshore operations. This prerequisite was crucial as it ensured that the individuals involved possessed the necessary skills and knowledge to execute their tasks effectively and safely.

The core objective of logistics planning was to guarantee the availability of personnel with the requisite expertise and training for their respective roles. This encompassed a meticulous evaluation of the skill sets needed for each element of the project. For instance, personnel responsible for underwater tasks needed to have diving expertise, while those managing safety had to be well-versed in safety protocols and procedures. These limitations called for hiring specialists in each field.

The influence of logistics on design procedures cannot be overstated. Elements such as personnel availability, safety training, and medical approvals had to be seamlessly integrated into the design process. This integration was crucial to ensure that the structures (MUCL elements) were not only functional but also accessible and compatible with the planned activities. In essence, logistics served as a cornerstone in determining the feasibility and efficiency of the design procedures, making it an indispensable aspect of the overall project planning and execution.

Nevertheless, there were notable limitations tied to the existing design procedures. These limitations influenced the design and execution of specific tasks, requiring alternative approaches to achieve the desired outcomes while adhering to regulations.

Another factor impacting logistics planning was additional measures to ensure strict adherence to safety regulations. The need for enhanced security and control added complexity to the logistics planning process, as it demanded the seamless integration of safety protocols and access management within the overall project design.

Thus, while logistics presented challenges, they also provided opportunities for problem-solving and refining the project's design to meet its objectives effectively.

Accessibility

Accessibility for each MUCL element is a multifaceted consideration that significantly impacts the overall design procedures. It hinges on the requirements made by the government. These start with vessels employed during operations, that have to meet administrative approval standards. The same is true for the crew members, that have to hold certain certificates such as offshore medical certificates and Sea survival training certification and if choosing to visit the site by helicopter additional trainings are mandatory.

The governmental prerequisites limit the pool of workers and also of contractors capable of working in with and on the offshore installation. Hence careful research and planning has to be done to combine the governmental requirements and the biological requirements as the systems have to be installed at certain times to be ready during the peak performance of mussel and algae.

The limitations of current design procedures in the emerging field of multi-use systems revolve around the scarcity of specialized generalists, the complexity of permitting and certification requirements, the need for interdisciplinary training, integration challenges, and the imperative for knowledge transfer and skill development. These constraints underscore the necessity for comprehensive strategies to address limitations and facilitate the effective development and deployment of multi-use systems.

Maintenance operations

Maintenance operations were established to ensure the proper functioning and longevity of the systems. A remote-controlled camera was utilized for easy and low-cost inspections of underwater equipment and mussel growth, allowing for effective monitoring.

The maintenance trips were planned and coordinated through close communication between the shipping company, FINO3 offshore engineering team, and the FuE UNITED team. However, due to the weather conditions at FINO3, many trips had to be arranged on short notice and occasionally postponed. To maintain flexibility in coordinating these trips, it was evident that thorough preparation and easy-to-follow protocols were essential. The Decision Support System (DSS), UNITED Deliverable 2.5 (D2.5) facilitates the planning of future maintenance trips.

Different structures at FINO 3 required specific maintenance procedures. For continuous porpoise detectors (CPODs), the maintenance involved recovering the CPODs, cleaning the housing, and replacing memory cards and batteries. Side marking buoys required the replacement of lost buoys due to storm damage, with transportation from the shore to the operational harbour. Visual inspections of mooring components and buoys were conducted during CPOD maintenance.

The mussel system maintenance included visual inspections of buoys from the ship and diving inspections during lander installation. The diving inspections involved examining mussel growth, mooring chains, and buoy attachments. Video inspections utilizing a simple remote underwater camera were conducted during CPOD maintenance trips to inspect mussel growth.

For the seaweed system, maintenance tasks included visual inspections of the seeded seaweed net in the harbour before offshore deployment, cleaning the seaweed net following a failed algae trial due to poor water quality, and re-seeding the seaweed net just before offshore deployment.

Maintenance operations influenced the design procedures by necessitating considerations for easy access and inspection of the MUCL elements. The choice to use a remote-controlled camera for inspections demonstrates the importance of incorporating practical and cost-effective maintenance methods into the design. Additionally, the need for coordination with various teams and the establishment of efficient protocols highlighted the significance of planning for maintenance activities during the design phase.

Design procedure limitations and improvements

Several key limitations and challenges exist. The primary problem in the German pilot is the remote location 80 km off the coast, which is difficult and expensive to access. This makes the usage of a nearshore site crucial, despite differences in water depth and salinity, limiting testing to material and sensor components and scaled models rather than the real system. One other major limitation is the absence of specific standards for offshore mussel and seaweed cultivation systems, requiring verification by an independent company to assess system dynamics and equipment failure risks. Lack of standardized guidelines influenced the design process, necessitating alternative approaches to meet regulatory requirements. Also, safety regulations added complexity to logistics planning, requiring integration of safety protocols and access management. Due to the novelty of multi-use approaches a shortage of specialized generalists exists. Adding complexity and calling for interdisciplinary training. Weather-related postponements and the need for short notice, is also emphasizing the need for thorough preparation and tools like the Decision Support System to optimize future maintenance planning.

Based on the limitations and challenges presented for the German pilot, we suggest the following improvements:

- Development of Industry Standards: Work towards the establishment of industry-specific standards for offshore mussel and seaweed cultivation systems. This would provide clear guidelines for design, construction, and operation, reducing the reliance on ad-hoc approaches.
- Research and Testing Facilities: Invest in research and testing facilities that mimic the offshore conditions as closely as possible. This would enable more comprehensive testing of components and systems before deployment, reducing the uncertainties associated with nearshore testing.
- Interdisciplinary Training: Implement training programs that promote interdisciplinary collaboration among professionals involved in the design and operation of these systems. This can help bridge knowledge gaps and enhance problem-solving capabilities.
- Advanced Modelling and Simulation: Develop advanced modelling and simulation tools to predict system behaviour in various environmental conditions. This would allow for virtual testing and optimization of system components and configurations.
- Risk Assessment and Management: Establish a comprehensive risk assessment and management framework that identifies potential risks associated with equipment failure, safety, and logistics. This would enable proactive risk mitigation measures.
- Technology Integration: Explore opportunities for integrating emerging technologies, such as automation, remote monitoring, and artificial intelligence, to improve system performance, reduce operational costs, and enhance safety.
- Collaborative Research: Foster collaboration with research institutions, universities, and industry partners to gain access to expertise and resources, enabling innovation and problem-solving.
- Adaptive Maintenance Protocols: Develop adaptive maintenance protocols that can accommodate short-notice planning and weather-related delays. Utilize predictive maintenance techniques to minimize downtime.
- Knowledge Transfer: Create structured knowledge transfer programs to ensure that experiences and lessons learned are effectively passed on to new team members, reducing the impact of turnover.
- Regulatory Engagement: Engage with regulatory authorities to advocate for the development of specific regulations and permitting processes tailored to offshore mussel and seaweed cultivation systems.
- Environmental Impact Assessment: Conduct thorough environmental impact assessments to understand the potential effects of these systems on the surrounding ecosystem and make design adjustments accordingly.
- Public Awareness and Stakeholder Engagement: Involve local communities, environmental organizations, and other stakeholders in the design and planning process to address concerns, gather input, and build support for these projects.

By implementing these improvements, the design procedures for offshore mussel and seaweed cultivation systems can become more robust, efficient, and adaptable, ultimately facilitating their effective development and deployment while addressing the identified limitations.

MUCL for offshore cultivation, particularly those involving mussel and seaweed farming, offer substantial potential for synergies that benefit both the environment and industry. By capitalizing on nutrient cycling, shared infrastructure, and co-harvesting, these systems can enhance ecological resilience, optimize resource utilization, mitigate environmental impacts, and improve operational efficiency. Moreover, these synergies underscore the importance of interdisciplinary collaboration and knowledge exchange, fostering innovation in the emerging field of multi-use systems. As research and development in this area continue, harnessing these synergies will play a pivotal role in advancing sustainable offshore cultivation practices.

2.2. Benefits, risks and limitations

Located 80 kilometres offshore, the German Pilot offers a unique chance to investigate the advantages, drawbacks, and restrictions of offshore multi-use agricultural systems. The advantages are numerous and include industry innovation, operational effectiveness, and environmental sustainability. In addition to improving the overall ecological resilience of the offshore environment through nutrient cycling, the integration of mussel and algae systems provides common infrastructure that maximizes resource usage and reduces environmental consequences. Based on the above information and on UNITED D7.4 (2022), D7.5 (2023) the benefits and synergies are being described below:

Benefits

In terms of benefits, the mutual interaction between mussel and algae systems promotes nutrient cycling, enhancing the overall ecological resilience of the offshore environment. This symbiotic relationship contributes to the health and balance of the marine ecosystem. Additionally, by sharing infrastructure and co-harvesting, the German Pilot maximizes resource utilization, reducing operational costs and environmental impact. The challenges faced, such as the remote location and absence of specific standards, have driven innovation in design procedures. The development of industry-specific standards and advanced modelling tools demonstrates a commitment to overcoming obstacles and fostering long-term sustainability.

Risks

Still, there are risks associated with the pilot. Because of its remote location, careful logistics planning is required due to operational challenges. Postponements due to inclement weather and short-notice agreements introduce complexity and may affect the regularity of maintenance tasks. Uncertainties are introduced by the lack of specific standards for offshore systems that cultivate seaweed and mussels; additionally, the use of ad hoc approaches and the requirement for an independent assessment to confirm system dynamics highlight potential risks related to equipment failure. Logistical limitations are introduced by stringent government requirements for personnel and equipment. Additionally, the deployment and accessibility of personnel are complicated by the need for specialized certifications and adherence to safety protocols.

Limitations

Moreover, several limitations are evident. Due to the challenges posed by the offshore location, testing is limited to material and sensor components, as well as scaled models. This limitation constrains the ability to validate the real system under true offshore conditions. The scarcity of specialized generalists calls for interdisciplinary training, bridging the knowledge gap among professionals involved in the design and operation of these systems. The absence of specific regulations tailored to offshore mussel and seaweed cultivation systems hinders seamless project execution, emphasizing the necessity of engaging with regulatory authorities to develop a regulatory framework that aligns with the unique characteristics of multi-use systems.

Synergies

Despite challenges and risks, the German Pilot highlights synergies achievable through interdisciplinary collaboration, design innovation, and a dedication to sustainability. A notable positive outcome is the reduction of CO2 emissions by combining maintenance trips, showcasing potential synergies in aquaculture facilities supporting fish habitats, possibly increasing fish abundance. Mooring equipment acts as artificial reefs, enhancing ecosystems. Algae and mussel cultivation positively affects nutrient content in the water.

3. DUTCH PILOT

The Dutch pilot is located 12km off the coast of Scheveningen, The Hague. Therefore, it has the offshore conditions you can find in a wind park, but not the long travel time. North Sea Farmers has a permit for multi-use pilots at this location, so no additional permit process was needed. This makes it a perfect location for a pilot project like UNITED. See for impression Figure 2.

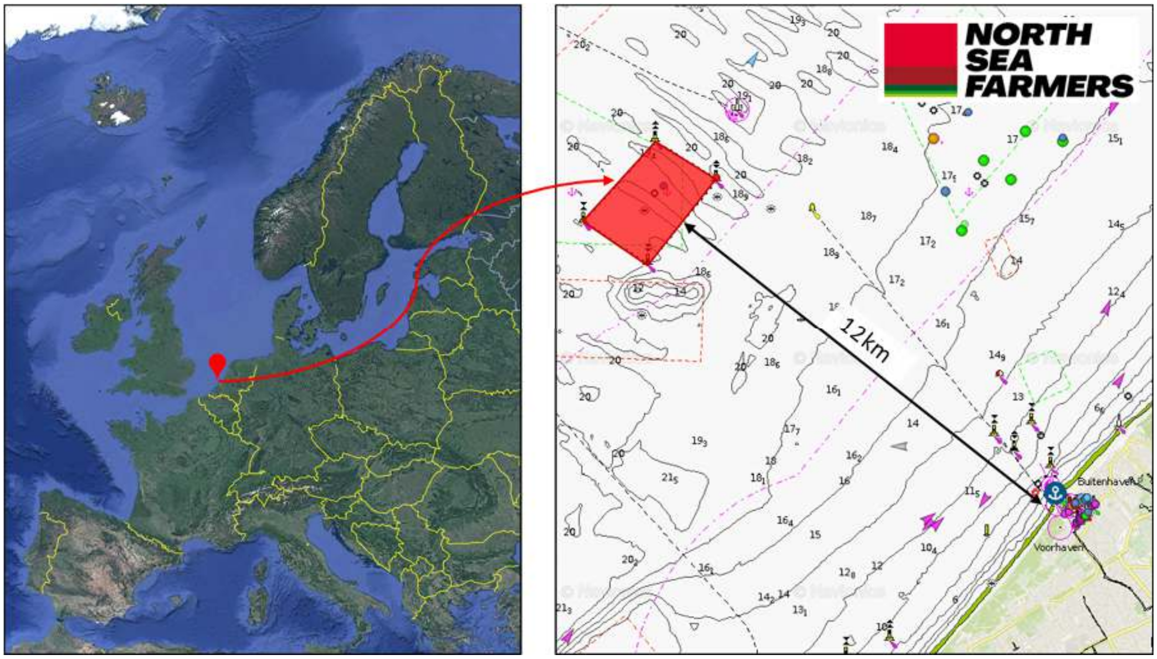

Figure 2: Location of the Dutch pilot at the North Sea Farmers Offshore Test Site 12km of the coast

The two multi-use activities that are combined in the Dutch pilot are offshore seaweed cultivation and floating solar, both with the goal to scale-up the farm within an offshore wind farm. Figure 3 shows an impression of the installations at the Dutch pilot location.

Figure 3: Impression Dutch pilot with seaweed cultivation (left) and floating solar (right)

3.1. Technical information

Environmental parameters

The Dutch Pilot project considers several environmental parameters that have an impact on the performance and design of the MUCL elements. These parameters include wind speed, wave action, currents, water temperature, salinity, oxygen content, and more. Here's a breakdown of their description and impact:

Wind Speed: The wind speed in the offshore test site affects the structural integrity and stability of the solar farm pilot. It determines the loading on the floating platforms and the solar panels' exposure to wind forces.

Wave Action: Wave action, characterized by parameters such as significant wave height, affects the structural integrity and stability of various MUCL elements. It influences the design of floating platforms, moorings, and buoys, considering their ability to withstand wave-induced loads and motions.

Currents: The direction and strength of currents impact the design and positioning of the seaweed and mussel systems. Current forces influence load distribution, mooring chain design, and attachment points for buoys and platforms.

Water Temperature: Water temperature variations affect the growth and survival of seaweed and mussel spat in the respective systems. Different species have specific temperature requirements, and the systems need to provide suitable conditions for their development.

Salinity: Salinity variations can influence the growth and survival of seaweed and mussel spat. The systems must maintain appropriate salinity levels to support the desired species and optimize their production.

Oxygen Content: The oxygen content in the water is crucial for the survival of marine organisms and the overall ecological balance. Monitoring and maintaining sufficient oxygen levels are necessary to ensure the health and productivity of the seaweed and mussel systems.

The impact of these environmental parameters on each MUCL element is significant. They influence the structural design, positioning, and performance of floating platforms, moorings, buoys, and the overall layout of the installations. The systems must be designed to withstand environmental loads, provide suitable conditions for growth and survival, and optimize resource utilization.

The offshore test site where the Dutch Pilot is located experiences specific environmental parameters. The site is exposed to offshore conditions with a significant wave height (Hs) of 5m. The water salinity ranges between 34-35 ppt, and the temperature varies from a minimum of 3 °C to a maximum of 18 °C. The current follows a NE-SW direction. It's important to note that the salinity, temperature, and stratification in this region are heavily influenced by freshwater input from the Maas and Rhine Rivers, leading to complex hydrodynamics in the area.

These environmental parameters have significant impacts on each MUCL (Multi-Use Combined Layout) element. The wave action, characterized by a significant wave height of 5m, affects the structural integrity and stability of the installations, such as the CPODs, side marking buoys, and seaweed system. The currents, following a NE-SW direction, influence the design and positioning of the mussel and seaweed systems, as well as the load distribution on mooring chains and buoy attachments. Water temperature and salinity variations affect the growth and survival of seaweed and mussel spat in the respective systems.

The current design procedures for the Dutch Pilot have some limitations in addressing the environmental challenges and requirements. These limitations include:

Lack of Mooring Force Measurements and Remote Monitoring: The absence of mooring force measurements and remote monitoring systems hinders the accurate assessment of the forces experienced by the MUCL elements. Incorporating these measurements would provide valuable data for design optimization and system performance evaluation.

Damage Due to Extreme Environmental Weather Conditions: The MUCL elements are susceptible to damage caused by extreme weather conditions. Design procedures should account for these conditions to ensure the robustness and durability of the installations.

Consideration for Operation, Serviceability, and Intervention: Design procedures need to account for the operational aspects of the installations, including accessibility for maintenance and interventions offshore. Ensuring ease of operation and serviceability contributes to the long-term success of the MUCL systems.

Spatial requirements

The MUCL elements at the Dutch Pilot site have specific spatial requirements. The offshore site itself spans 6km², with six research plots of 1km² each. Plot 2 accommodates the solar farm pilot, while Plot 3 is dedicated to the seaweed farm pilot. The seaweed farm consists of two system setups based on moored spar-buoys with production nets in between. One system is aligned with the tidal currents, while the other is oriented perpendicular to the current. The spatial orientation of the seaweed farm aims to investigate the impact of light availability on yield.

The spatial requirements have an impact on the design procedures, as they dictate the arrangement and layout of the MUCL elements within each plot. The positioning of the solar panels and seaweed nets within the plots needs to consider factors such as light exposure, accessibility for maintenance, and potential interactions between different elements. The spatial requirements influence the overall layout and configuration of the installations, requiring careful planning and optimization to maximize efficiency and resource utilization.

However, there are limitations to the current design procedures. The existing procedures may not fully account for the spatial interactions and optimization possibilities among the MUCL elements. Additionally, the design procedures may not adequately address the dynamic nature of the offshore environment and the need for adaptability in response to changing conditions. Enhanced design methodologies and analysis tools are necessary to overcome these limitations and improve the effectiveness of spatial planning for MUCL projects.

Design Structural Lifetime

The design structural lifetime refers to the expected lifespan of the structures used in the MUCL installations. The determination of the design lifetime involves considering various factors such as structural integrity, material durability, and environmental loads. In the context of the Dutch Pilot, specific considerations are made to ensure the longevity of the installations.

The impact of the design structural lifetime on design procedures is crucial. The expected lifespan of the structures influences decisions regarding material selection, construction techniques, and maintenance plans. It affects the overall cost-effectiveness, safety, and sustainability of the installations. Design procedures must incorporate accurate assessments of the structural lifetime to ensure the longevity and reliability of the MUCL elements.

Logistics planning

The logistics planning for the Dutch pilot, encompassing offshore seaweed cultivation and floating solar energy, involves intricate considerations for each multi-use element. For offshore seaweed cultivation, logistics planning encompasses the transportation of seeding materials, maintenance equipment, harvesting tools, and ensuring access for monitoring and harvesting activities. In the case of floating solar panels, logistics planning includes the transportation, installation, and maintenance of solar panels, anchoring systems, and electrical components.

These distinct logistical requirements impact the design procedures by necessitating careful spatial arrangement, structural considerations, and access pathways on the platform. The integration of multiple activities within the limited space of the platform poses a challenge to the current design procedures, primarily regarding optimizing layouts to accommodate diverse activities efficiently. There are limitations in the current design procedures that need improvement to ensure seamless incorporation of logistics planning for both offshore seaweed cultivation and floating solar, particularly in streamlining the coordination of activities, optimizing spatial distribution, and addressing maintenance and accessibility concerns in a comprehensive manner.

The logistics planning for the Dutch pilot involves intricate considerations for each multi-use element, particularly in the context of the test location situated 12 kilometres offshore. The remote offshore location significantly influences logistical operations, requiring meticulous planning for transportation, accessibility, and maintenance due to the distance from the shore. This involves coordinating vessel schedules, securing specialized equipment capable of withstanding offshore conditions, and ensuring robust logistics infrastructure to support regular maintenance and operations at a considerable distance from the coastline. The offshore positioning also amplifies the impact of logistics planning on design procedures, emphasizing the need for resilient, weather-resistant infrastructure, and optimized layouts to mitigate the challenges posed by the offshore environment. However, the remote-ness of the test location offshore poses distinct challenges to the current design procedures, warranting improvements to effectively incorporate logistics planning for both offshore seaweed cultivation and floating solar, specifically tailored to offshore conditions and remote operational requirements.

Accessibility

The accessibility considerations for the Dutch pilot site present critical challenges that significantly influence logistics planning for each multi-use element. Access to the remote offshore location necessitates comprehensive logistical arrangements, including vessel transportation for personnel, equipment, and materials, while factoring in weather conditions and sea states that might impact travel times and safety.

For offshore seaweed cultivation, accessibility planning involves ensuring convenient access for seeding, monitoring, and harvesting activities, requiring reliable pathways and infrastructure that can endure the offshore environment. Similarly, for floating solar panels, accessibility planning encompasses installation, maintenance, and potential repairs, demanding specialized equipment and safe navigation routes.

The logistical demands, particularly due to the remote offshore position, profoundly impact design procedures by emphasizing the need for robust, resilient infrastructure capable of withstanding offshore conditions and providing safe access for operations.

Maintenance operations

Maintenance in the Dutch pilot is depending on the seasons. The seaweed cultivation pilot has two growing seasons. During a growing season, no other than the operational & monitoring work was executed: installation, monitoring, harvesting. After the harvest of the first season (May 2021), the main structure was kept in place offshore. Before the next growing season, a check and necessary maintenance of the whole offshore installation has taken place. The cultivation nets were brought to land, where they were cleaned and replaced by a different type of net / substrate for the next growing season.

The operation of the floating solar pilot is part of another project. In general, this installation is currently being extended step by step towards a 1 MW. This project will continue beyond UNITED to an even larger scale.

Design procedure limitations and improvements

The synergies in the Dutch pilot:

- Using the same type of vessels for the offshore work and when possible, joining activities in one offshore trip.
- Using the same type of anchors for the offshore installations, sharing experiences on procurement, installation and calculations.
- Sharing knowledge on monitoring equipment and sharing the retrieved data.
- In potential (not yet executed in this pilot): using the floating solar panels for supply of energy for monitoring equipment of the seaweed farm.

Next to the synergies we encountered at the Offshore Test Site pilot, there are synergies for combining seaweed cultivation and floating solar with offshore wind. The potential on economic & social level will be discussed in WP3. To give some examples, the wind turbines protect the seaweed and floating solar farm from infringement of vessels. The floating solar farm can be connected to the same electricity cable, and therefore increase the efficiency.

Cultivating seaweed within a wind farm can increase the biodiversity within the wind farm and therefore contribute to the required nature-based solutions within a wind farm. Having more than one type of multi-use could ensure that no monocultures are created with negative effects, of course if deployed in a right way.

3.2. Benefits, risks and limitations

The Dutch Pilot, operating within a dynamic offshore environment, presents a nuanced landscape of benefits, risks, and limitations associated with its MUCL elements. Based on the above information and on UNITED D7.4 (2022), D7.5 (2023) the benefits and synergies are being described below:

Benefits and synergies

One significant advantage lies in the strategic utilization of environmental parameters. The meticulous consideration of wind speed, wave action, currents, water temperature, salinity, and oxygen content allow for the creation of robust MUCL designs. The focus on structural integrity in the face of a substantial 5m wave height at the offshore test site underscores the commitment to systems capable of withstanding challenging conditions. Moreover, the spatial requirements for each MUCL element within the expansive offshore site contribute to optimized resource utilization and efficiency.

Synergies play a pivotal role in enhancing benefits. By utilizing the same type of vessels, anchors, and knowledge across offshore activities, the Dutch Pilot achieves operational and economic efficiencies. The potential combination of seaweed cultivation and floating solar with offshore wind further presents opportunities for increased biodiversity, economic efficiency, and nature-based solutions. This collaborative approach extends to the gradual extension of the floating solar pilot, contributing to a larger-scale project beyond the scope of UNITED.

Risks

Despite the strategic planning, the Dutch Pilot is not immune to risks. Environmental challenges such as extreme weather conditions pose threats to the structural integrity of MUCL elements. The absence of mooring force measurements and remote monitoring systems introduces uncertainties, hindering accurate assessments of the forces experienced by the installations. Lack of real-time monitoring for specific parameters, like mooring forces, further adds to the risk profile, limiting insights into the performance and behaviour of the installations.

Additionally, the complex hydrodynamics influenced by freshwater input from the Maas and Rhine Rivers create a unique set of challenges. These challenges include variations in water salinity, temperature, and stratification, necessitating continuous monitoring and adaptive design methodologies to address uncertainties.

Limitations

The Dutch Pilot grapples with certain limitations in its current design procedures. The spatial requirements, while carefully considered, may not be fully optimized for interactions among MUCL elements. The existing design methodologies may not fully account for the dynamic nature of the offshore environment, demanding continuous adaptations to changing conditions.

Moreover, the lack of common data collection and a unified dashboard solution complicates the gathering and analysis of data from different MUCL elements. The current design procedures also fall short in addressing specific operational and maintenance requirements for each MUCL element. The absence of real-time monitoring for certain parameters poses challenges in ensuring timely interventions and adjustments. This type of limitation was solved with the use of a common platform, namely HiSea.

4. BELGIAN PILOT

The Pilot is situated in the Belgian part of the North Sea (BPNS), more specifically in the offshore wind farm of Belwind, operated by Parkwind. The BPNS is characterised by a system of submerged sandbanks and gullies, which are predominantly formed and sustained by the tidal currents. The offshore wind farm area is situated at the eastern border of the BPNS, and includes three sand banks (Bligh Bank, Lodewijkbank and Thortonbank) and the adjacent gullies.

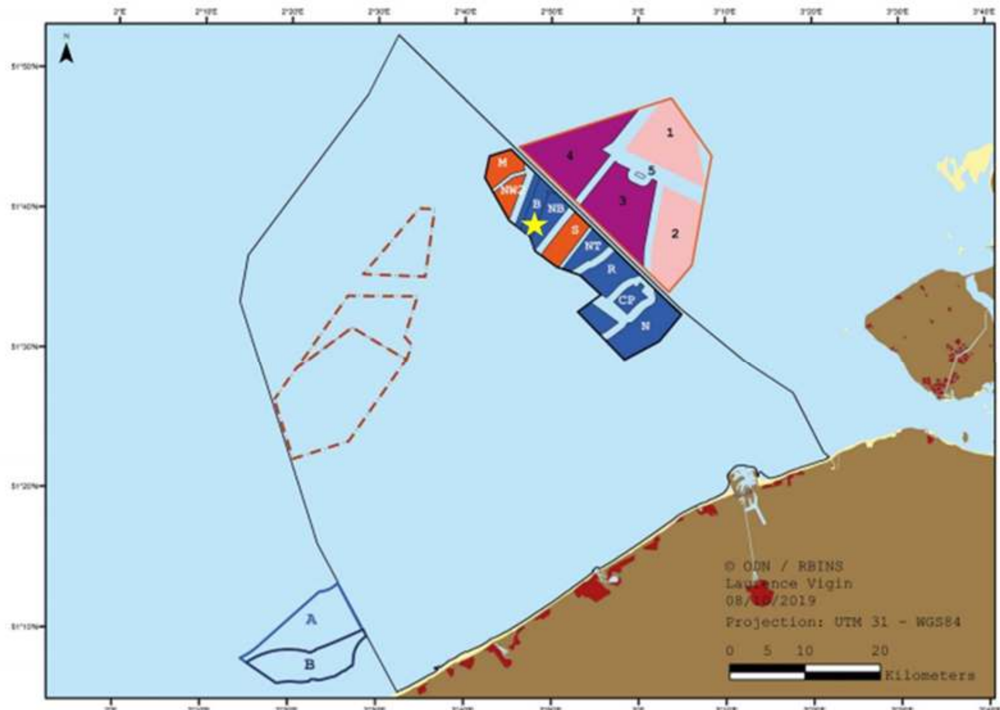

Figure 4. Belgian part of the North Sea with realised and planned offshore wind farm concessions - The approximate position of the Pilot site (at the offshore wind farm of Belwind, operated by Parkwind) is indicated by the yellow star.

4.1. Technical information

Environmental parameters

The seabed has a depth between 15 and 37 m. The Bligh Bank is part of a system of tidal banks and belongs to the Hinderbanks. Both banks and gullies are characterized by the presence of mobile sand dunes. Bligh Bank has a steep eastern side and a more gentle-sloping western side. Sand is the pre-dominant sediment, with a grain size of 300-350 µm and a maximum of only 1 % clay. The gully may contain coarser gravel-sands.

Mean (surface) current velocity at Bligh Bank is 0.55-0.57 m/s, and while in the deeper gullies the mean current velocity is lower, maximum current velocity (up to 1.09 m/s) is higher in the gullies than at the sandbanks. In general, current velocity ranges between 0.25-0.95 m/s. Significant wave height is 5.8m, wave peak period: 10.6s, wave direction: 330deg (coming-from), maximum single wave height: 11.2m. The current magnitude is 1.0 m/s (depth-averaged) and the associated direction: 60deg (going-to).

Seawater

In the BPNS, including the Pilot site, mean seawater temperature is 11 °C, which can increase up to 19 °C in summer and decrease down to 0.05°C in winter. Salinity of the seawater ranges between 31 and 35 ppt. Suspended particulate matter content in the offshore BPNS, including the Pilot site, is low, around 4 mg/L.

Atmosphere and climate

Belgium has a temperate oceanic climate. The coldest month has a mean temperature of 3 °C, while the hottest month a mean temperature of 16.9°C. Mean rainfall ranges between 50 and 80 mm/month. At sea, the dominant wind direction is west-south-west, with a mean speed of 9.6 m/s. No relevant statistics on atmosphere (air quality related to pollution) are available for the BPNS, as no measuring station is present at sea, only land-based stations. However, it can be assumed that the air quality at sea is satisfactory at least.

Remote real-data collection was not conducted in the Belgian Pilot. However, data from various sources was collected and utilized, including:

- Oceanographic variables extracted from Copernicus marine satellite (Sentinel2/3) and model (ERSEM, DCSM Deltares) products. These freely available products offered hind cast, real-time, and 3-month forecast data on variables such as chlorophyll a, suspended solids, salinity, temperature, alkalinity, current speed, wave height, and shear stress.
- Weather forecast data obtained from Windguru, focusing on important variables like wind speed, wave height, and weight period.
- Tidal information and sediment data extracted from EMODNET.

Additionally, experimental variables were monitored through sampling missions, which included:

- Oyster growth measurements such as shell length, shell weight, total weight, and tissue weight.
- Fouling observations, including species composition, estimation of species cover, and the presence of non-indigenous species.
- Seaweed measurements, specifically seaweed length and seaweed weight.
- Oyster settlement assessments, involving the number of settled spat, survival rate, and size measurements.

Numerical models were established and validated using field measurements. Two types of numerical models were developed and connected to satellite products, ERSEM data, and DCSM data:

- DEB models (Dynamic Energy Budget) for the European flat oyster, allowing predictions related to growth, fitness, survival, reproduction, and nutrient budgets at an individual level.
- DEB population models for the European flat oyster, enabling predictions regarding population dynamics.

These models were applied to 10 years of geospatial data for the North-Atlantic, Channel, and North Sea regions. Oyster samples were collected to gather information on growth, fitness, reproductive status, disease status, and fouling of the organisms.

However, no monitoring of physical and biochemical parameters took place.

The major constraint for aquaculture offshore in the Belgian part of the North Sea, are the extreme weather conditions (UNITED D1.1, 2020). Waves of 6m are not an exception as are currents of 1m/s. The very corrosive environment of seawater discourages the use of steel (like anchor chains) and encourages the use of ropes.

In the design of the final backbones, both for seaweed and oyster, the largest waves and strongest currents occurring in a 50-year period have been used to calculate the necessary dimensions of anchors, mooring ropes and backbones, while in addition, a safety factor of 3.45 has been applied (UNITED D7.2, 2022).

Spatial requirements

The spatial requirements for each component of the Multi-Use Offshore Platform (MUOP) were carefully considered and planned during the installation process. In June 2021, four restoration structures with nature-inclusive scour materials were installed on the scour protection layer of two monopiles. These structures were strategically placed in different directions, with two structures at each monopile, one in the north-east direction and the other in the south-east direction.

The spatial requirements of the MUOP elements had a significant impact on the design procedures. The design had to take into account the specific positioning, orientation, and arrangement of the structures to ensure their optimal functionality and compatibility with other components. This required careful coordination and integration of various spatial considerations.

Another crucial aspect related to the spatial requirements was the design structural lifetime of the structures. Factors such as durability, stability, and longevity in the offshore environment were taken into account during the planning phase. The determination of the design lifetime involved considering various parameters, including weather conditions, tidal information, and potential risks associated with offshore operations.

The design structural lifetime had a significant impact on the design procedures. It influenced decisions regarding the selection of materials, construction methods, and maintenance requirements. The design procedures had to address the structural integrity and longevity of the components, ensuring that they could withstand the harsh offshore conditions and fulfil their intended purpose throughout their designated lifespan.

However, it is important to note that the current design procedures may have certain limitations when it comes to adequately addressing the design structural lifetime requirements. The challenges faced during the installation and the need to recover and reinstall certain structures underscore the importance of continuously evaluating and refining the design procedures to overcome these limitations.

Logistics planning

Logistics planning for each MUCL element, specifically algae culture, oyster culture, and oyster restoration efforts in the Belgian Pilot, involved several considerations. The staff involved in these activities had to meet certain pre-requisites, including specific training for offshore work, as described in documents UNITED D6.1 (2021) and UNITED D6.2 (2023). The logistics planning ensured that the necessary personnel with the required expertise and training were available for the respective tasks.

The impact of logistics on design procedures was significant. The planning of logistics, such as personnel availability, safety training, and medical approvals, had to be integrated into the design process. The design of the MUCL elements had to accommodate the logistical requirements, ensuring that the structures were accessible and compatible with the planned activities. Logistics played a crucial role in determining the feasibility and efficiency of the design procedures.

Accessibility

Vessel requirements: In general, the vessel used for operation must be (i) administratively approved by maritime authority, this means that the owner has to complete the SOS system (Safe Offshore Operations System). This includes general vessel info and vessel documentation/certificates. In addition, (ii) the vessel will be inspected (vessel vetting) if the inspection was not done before or has expired. In terms of equipment on board, the following items should be present:

- Each vessel shall have an operational SOLAS approved Class A AIS system whenever working at the project.
- The crew vessel should have an operational mobile phone on board through which the bridge is continuously accessible. The phone shall be dedicated to the specific vessel and -in Belgium- use the Base network or have a foreign subscription.
- Each crew vessel shall upon request have two (2) seats for employer's staff available.
- The vessel’s radio communication equipment shall be GMDSS compliant.
- The contractor shall ensure that all information requirements from authorities on vessel movements are met and available 7 days before start of the works.

- Each crew vessel shall have an operational signal receiver and direction finder operational frequency 121.5Mhz for Personal Locating Beacons (PLB) of a type such as "sea marshall" and/or equivalent AIS PLB.

Requirements for crew.

A transfer plan is prepared in advance which includes personal and training info of the crew members. This includes the ID, the personal profile that was created online in the SOS system, medical offshore certificate, certificate Sea survival training (minimum STCW), certificate of successful general Parkwind induction training. A document is available that describes the required minimum training level of the people onboard.

Requirements to deploy activities.

Work permit: Every sampling activity needs to be described in detail by the partners that will carry out the sampling and needs to be approved by Parkwind, and more specifically by the department HSSE (Health Safety Security and Environment). This document, called the Risk Assessment and Method Statement (RAMS), describes in detail which activities will be carried out and how (e.g. use of crane, A-frame, position of the boat during activities, actions to be taken in case of risks) taking all Parkwind requirements into account. When diving activities are planned, a diving plan needs to be provided (before activity) while a dive checklist and completed logbook needs to be provided after the activity.

Maintenance operations

Maintenance for aquaculture was scheduled at the following time-points:

• For seaweed aquaculture: None. There was only the installation, intermediate sampling, and harvesting. The buoys of the longlines were, of course, cleaned together with the ones from the oyster long-line.

• For oyster aquaculture: The buoys were visually inspected when the seaweed line was sampled. Upon the harvest of the seaweed, a first cleaning mission of the lines was conducted. Then, two more cleaning and sampling missions were carried out for the oyster line, one in summer and one upon the removal of the structures in October.

4.2. Benefits, risks and limitations

The Belgian Pilot, nestled in the Belgian part of the North Sea within the Belwind offshore wind farm, presents a unique interplay of benefits, risks, and limitations associated with its MUCL elements. Based on the above information and on UNITED D7.4 (2022), D7.5 (2023) the benefits and synergies are being described below:

Benefits

One notable benefit arises from the shared use of crew vessels for monitoring and maintenance activities. The vessels, equipped for offshore work, serve multiple purposes by visually inspecting buoys, checking the aquaculture longlines, and ensuring the overall well-being of the offshore installations. This synergy optimizes fuel costs and promotes efficient use of resources.

This collaborative approach extends to installation and sampling missions for both seaweed and oyster activities. By consolidating missions, including the inspection of oyster longlines during seaweed sampling, the pilot attains operational efficiency. The same vessels and missions serve dual purposes, streamlining efforts and reducing logistical complexities.

The seasonal requirements of oysters and seaweed create a symbiotic relationship, ensuring year-round boat utilization. Oyster harvesting in summer and seaweed harvesting in winter align seamlessly with the wind park's year-long maintenance needs. This harmony facilitates continuous boat use for maintenance, checks, and harvesting, optimizing operational effectiveness.

Risks

The Belgian Pilot contends with the challenges of extreme weather conditions, including waves reaching up to 6m and currents of 1m/s. The corrosive nature of seawater necessitates careful material selection, favouring ropes over steel in certain applications. The robust design, accounting for a 50-year wave and current scenario with a safety factor, mitigates these risks to a considerable extent.

Limitations

A significant limitation arises from restrictions on diving within the wind farm for aquaculture-related purposes. This constraint impacts the design and implementation of certain tasks, requiring alternative approaches and measures to adhere to safety regulations. The exclusion of tourists from the wind farm further adds a layer of complexity to logistics planning.

Moreover, the installation process shed light on the need for continuous evaluation and refinement of design procedures. Identified challenges and constraints during installation provided valuable insights for enhancing future designs. Continuous improvement in design methodologies is crucial to adapt to evolving operational requirements and optimize spatial arrangements.

Synergies

The synergy between oyster and seaweed activities, with complementary seasonal requirements, ensures year-round boat use. Oyster harvesting in summer aligns with seaweed harvesting in winter, facilitating continuous maintenance and checks on infrastructure throughout the year. This harmonized approach optimizes the use of boats and technical resources.

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5. DANISH PILOT

Middelgrunden was established on a natural reef with 3 to 6 metres water depth, 3.5km outside of Copenhagen harbour, in the fall of 2000. It is visible from Copenhagen city and surrounding beaches and tourist points of high value, like The Little Mermaid and the Round Tower. The offshore wind farm consists of twenty 2 MW turbines from Bonus Energy, now Siemens Gamesa Windpower, and is owned 50% by HOFOR (Copenhagen local energy and water supply) and 50% by the Middelgrunden Wind Turbine Cooperative with 8,553 members. It is the largest wind farm in the world based on cooperative ownership.

Figure 5. Location of Middelgrunden wind farm outside of Copenhagen harbour, Baltic Sea, Denmark

The wind farm consists of 20 turbines, each with a rated capacity of 2 MW. The maximum height of the wingtip is 102 meters. The electricity production is anticipated to be about 100 GWh a year. The turbines are erected on standard gravity foundations, which are placed on firm seabed after the upper layer of soft sediment has been removed.

5.1. Technical information

The Pilot site is located on the natural reef with 3 to 6 metres water depth. For more than 200 years up to 1975, the reef has been used as a dumpsite for harbour sludge and other contaminated waste. Middelgrunden site is heavily influenced by human activity in many respects. For example, the nearest area on land is characterised by technical installations, industry and harbour facilities. The closest recreational areas are the Middelgrunds Fortification (today called Ungdomsøen and operated by the Scout organisations) situated 1.3 km north of the wind farm and Amager Strand Park situated 2.5 km southwest of the wind farm. The island of Saltholm is situated 5 km southeast of the wind farm, with its surroundings it constitutes an international nature conservation area. Special environmental concern has been taken into consideration during planning and feasibility studies were carried out.

Environmental parameters

This pilot combines tourism activities to the wind farm with existing electricity production from offshore wind. Therefore, design and construction plans are not as elaborated as for other pilots because the offshore wind farm was already built in year 2000 and is out of the scope of UNITED. One of the main challenges in the design and construction of the wind farm relates to extreme weather conditions (including ice) that can occur at the pilot side.

In the organized tours, the unknown and changing weather conditions pose limitations on the access of tourists to the turbine foundation and tower. The combination of increasing wind, waves, and currents from a specific direction can make tourism visits impossible. These conditions are often unpredictable before departing from the harbour, and they can only be realized once offshore. Furthermore, the availability of only one ladder for accessing the turbine from the sea surface limits access possibilities. Rapid changes in weather conditions can also affect the safety and feasibility of boarding tourists back to boats, especially with small boats like zodiacs (RIB boats in Danish), due to unpleasant waves and currents.

To address these limitations, there are two possible solutions. The first is to use bigger boats that can navigate and approach the turbines independently of rapidly changing weather conditions. However, the choice of boat type is typically made in advance by the client, considering factors such as budget, schedule, and group size, which makes changing the boat type on the same day of the trip unrealistic. Another solution is to include more experienced and trained staff who can effectively deal with changing weather conditions. For example, the zodiacs owners have opted to have two crew members onboard instead of one to enhance safety and handling capabilities. Additionally, the availability of a forecasting system providing near-future forecasts of metocean conditions in the region of the wind turbine would allow boat operators to make informed decisions before the trip regarding the suitability of conditions for safe tourism visits.

Challenges include potential damage due to extreme weather conditions and ice risks at the Middelgrunden location. The ladder foundations of the Middelgrunden Wind Farm can be susceptible to damage from ice formation occurring every 5-6 years. To mitigate this risk, concrete gravity foundations with a bulbous shape are designed and built, facilitating ice breaking and easing the flow of ice around the wind turbine, thereby reducing loads on the foundation. The ladders are constructed with failure weakness so that only the lower parts of the ladder break off in the presence of ice, which minimizes the cost of repair work.

Spatial requirements

There is no special requirement in the co-location of the wind farm and the tourism activities. The wind turbines were already in place and the boat providing the tours either sail around the wind turbines or stop close to them at a distance that allows to board the boat through a dedicated ladder.

The requirements to the design, operation, maintenance and decommissioning of the wind turbines are not affected by the tourism activities. Tourism makes use of the existing infrastructure in the wind farm.

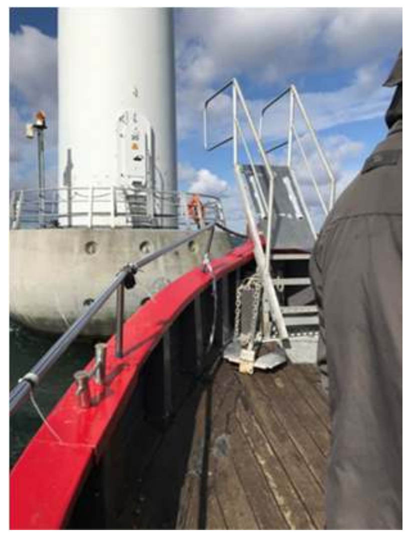

Figure 6: The boat approaching the wind turbine with the ladder.

Logistics planning

The Danish Pilot offers guided tours on a client basis. These tours are tailored according to the wishes of the clients. There are some physical and logistic boundaries (type of boat, tour duration, safety requirements i.e., type of shoes allowed, number of people in a boat, etc.) but clients can normally choose the time of departure and the date that the tour will take place.

Accordingly, every tour requires its own scheduling. The number of tours and visitors per year are continuously increasing (see Table 1), and most of them are concentrated in the spring and summer months. This number of tours, together with the high flexibility of the guides, allows a flexible scheduling system – based on boat and client's availability.

Table 1: Accumulated number of trips and guests from 2017 to 2023. Trips in 2023 cover only the first 6 months of the year

Business	2017	2018	2019	2020	2021	2022	2023*
Trips	31	35	48	4	13	75	67
Guests	676	930	1117	130	246	1687	1569
Turnover (kEUR)	38,9	44,3	55,6	4,4	19,5	102,1	111,7

Once a tour has been scheduled, the Danish Pilot uses own software to indicate whether a tour has been pre-confirmed, confirmed, paid or payment pending. This is internally shared among the guides involved in the Danish Pilot. Boat operators, which are subcontracted on a tour basis, are also flexible as they usually have more than one boat available. They are notified once the tour has been scheduled and confirmed.

There are two important facts to keep in mind on the scheduling of tours: the time of arrival after a tour, and the tours to be held in autumn and winter.

Usually, the time of arrival after a tour is only indicative and can actually not be known precisely. Arrival times are provided as tentative, as boat speeds depend on the water current, on the wind, and on the combination of both. Indeed, if the combination of both is not appropriate, we might only be able to sail to the turbines but without accessing them. And sometimes the whole tour gets cancelled because of storm / high wind conditions. Cancellations are done as soon as weather conditions are certainly known, or the captain cancels the tour.

In winter there are generally no tours. The main reason for this is the lack of tourism in Copenhagen during these months, but otherwise the tours could be organized. It is believed that in the winter and autumn, tours might be re-scheduled more frequently than in spring and summer. This is due to the seasonal variability of winds, which get stronger during this period of the year, limiting the access to the turbines. However, in year 2023 four tours have been cancelled: three of them in March, May and July due to too strong winds, and another one in August due to thunder.

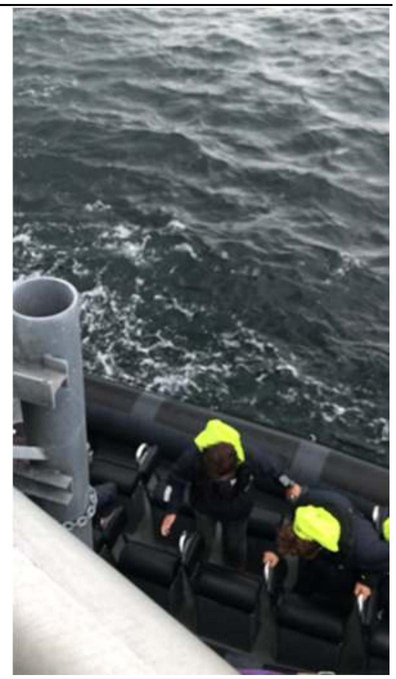

Figure 7: View of the boat from the wind turbine

One of reasons of creating the Virtual tours of the Danish Pilot has been to increase the opportunity of people visiting the wind turbines even in periods where the scheduling of the visits is not possible or very limited. This is, in the winter months. We acknowledge the importance of creating these tours to reach more public throughout longer periods of time.

Accessibility

Accessibility of visitors to the wind farm has to prioritize safety in all operations. This is achieved through two different means depending on the type of boat:

- Fisherman type boat: It has a dedicated ladder that allows the passenger to go from the boat to the foundation. The rule is only one person in the ladder at a time, free hands to use both rails, no hanging objects and all zips closed.
- Zodiac type: It uses a ladder sitting on the existing turbine foundation, on the lee of the farm. The boat secures its position with the motor and with a rope attached to the foundation, and one by one, passengers climb up the ladder up to the foundation. The rule is only one person in the ladder at a time, free hands to use both rails, no hanging objects and all zips closed.

  Since mid-2023 satisfactory surveys have been circulated and passengers have shown satisfaction in all the stages of the tour, including access to the wind farm, comfort in the boat, a comfort experience.

Maintenance operations

Maintenance activities in Middelgrunden Wind Farm can be divided into the maintenance of the offshore wind turbines, and maintenance of the boats used for carrying out the people out to the wind farm.

In both cases, maintenance activities are out of the scope of the Danish Pilot. Maintenance of the wind turbines are subcontracted to a third party, who own his own boat and has a specific contract with the turbine Cooperative on turbines' maintenance.

Maintenance of the tourism boats is the responsibility of the boat owners, also a third party. However, some lessons can be shared. What has been experienced is that if minor maintenance is being done in one of the turbines while there is an ongoing guided tour in the wind farm, this is actually not a problem. There are 10 turbines that we could potentially visit, so we just need to choose one turbine with no ongoing maintenance. And indeed, it can be an advantage for the group, as it could potentially get some extra knowledge and unique experience.

Design procedure limitations and improvements

The 3-year experience accumulated in the UNITED project for the Danish Pilot does not reveal limitations in the existing multi-use. Conversely, it benefits of the existing infrastructure of the wind farm. For example, visitors approaching the farm with a zodiac, make us of an existing ladder in the foundation which was originally set there for perhaps maintenance activities. This little design additions, very easy to implement during the inception of a project but very difficult to implement afterwards, are the ones that allow tourism activities in the wind farm.

If this project would be expanded to other locations, then other features had to be considered. The fact that the wind farm is only 3.5 km offshore makes it possible to visit in a 2-hour tour. Based on the tours organized throughout these years, it is seen that half of the participants are mainly interested in sailing around of the turbines, and do not necessarily aim at climbing up to the nacelle of the turbine. This said, and when planning for multi-use and to engage with local communities, it could be recommended to plan for sailing areas where trips around the turbines can be organized.

5.2. Benefits, risks and limitations

The Danish Pilot, centred around the Middelgrunden wind farm near Copenhagen, brings forth a range of dynamics shaped by its technical, spatial, logistic, accessibility, and maintenance considerations. Based on the above information and on UNITED D7.4 (2022), D7.5 (2023) the benefits and synergies are being described below:

Benefits

Tourism Integration with Offshore Wind

One of the unique aspects of the Danish Pilot is the seamless integration of tourism activities with existing offshore wind energy production. The wind farm, established in 2000, serves as a dual-purpose site, harnessing wind energy and offering guided tours. This integration promotes sustainable practices, utilizing existing infrastructure for diverse purposes.

Flexibility in Tour Scheduling and Growing Tourism

The Danish Pilot exhibits flexibility in tourism scheduling, catering to client preferences for departure times and tour dates. The continuous increase in the number of tours and visitors over the years, especially in the spring and summer months, underscores the appeal of this multi-use approach. The adaptable scheduling system enhances the overall accessibility and popularity of the wind farm tours.

Enhanced Accessibility and Safety Measures

Safety is prioritized in ensuring visitors' accessibility to the wind farm. Different types of boats, including fisherman and Zodiac types, employ dedicated ladders, allowing passengers to move from the boat to the turbine foundation safely. This thoughtful approach, combined with strict safety protocols, contributes to a positive visitor experience, as indicated by satisfactory surveys.

Risks

Weather-Dependent Tourism Challenges

The Danish Pilot faces challenges associated with unpredictable and changing weather conditions. The combination of increasing wind, waves, and currents can render tourism visits impossible, impacting the safety and feasibility of boarding tourists, particularly in small boats like Zodiacs. Rapid changes in weather conditions pose logistical and safety challenges for both tourists and operators.

Ice Risks and Structural Vulnerabilities

The geographical location of Middelgrunden exposes the wind farm to potential ice risks every 5-6 years. The ladder foundations of the wind turbines are susceptible to damage from ice formation. Mitigation measures include the design of concrete gravity foundations with a bulbous shape, facilitating ice breaking and minimizing the cost of repair work.

Limitations

Limited Design Considerations for Tourism

Given that the wind farm was established in 2000 and is beyond the scope of the current project, there are limitations in the detailed design and construction plans for tourism activities. The existing wind turbines and their foundations were not specifically designed for tourism, leading to challenges in optimizing visitor access and experience.

Weather-Induced Tour Cancellations

Weather conditions, particularly during autumn and winter, lead to the cancellation of tours. Stronger winds during these periods limit access to the turbines, resulting in rescheduled or cancelled tours. This seasonal variability poses a limitation in utilizing the wind farm for tourism throughout the entire year.

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6. GREEK PILOT

The Greek Pilot, denoted as the PATROKLOS Pilot site, is situated in the 59th km of Athens-Sounio Ave., Palaia Fokaia, Attiki, Greece, in the wider area of Cape Sounio (Figure 8). It includes an aquaculture unit situated in the Mediterranean Sea at the Greek coast. KASTELLORIZO operates a fish-farming unit on floating facilities in the marine area near island "Patroklos" (the island is located 850 metres from the coast). The wider area now is protected under NATURA 2000 and the Treaty of Barcelona due to a number of significant characteristics that this pilot site has. The pilot site for project UNITED is considered the wider area between the island and the mainland, with in between those two sites the fish farm. The multi-use activities that are taking place during the operational phase are the combined activities of the aquaculture unit with scuba diving tourist expeditions (Planet Blue diving center) facilitated by WINGS ICT Solutions monitoring system, namely AQUAWINGS.

Figure 8. Left and Middle: Proposed Pilot space, the yellow square depicts aquaculture unit (source: Google Earth). Right: Aquaculture unit and islet Patroklos on the opposite - Mediterranean Sea, Greece

6.1. Technical information

Environmental parameters

Within the Greek pilot, aquaculture production parameters are monitored in real time. These parameters are salinity, water quality, temperature, Dissolved Oxygen (DO), pH, electrical conductivity, total dissolved solids (TDS), turbidity, Chlorophyll-a, Nitrates (NO_3) and ammonium (NH_4). Furthermore, the co-location activities connectivity is monitored, and the aquaculture infrastructure by using underwater sensors, fish sensors, water quality sensors and meteorological sensors. Also, the sea transportations infrastructure is monitored (vessel movements and speed, meteorological sensors). By the use of underwater cameras, the fish behaviour and performance are monitored. Monitoring infrastructure continues in diving activities by using individual diver position sensor, mechanism for unexpected surface event such as rapid weather change or another incident. For the aquaculture infrastructure that are placed in great depths (such as anchors) a remotely operated vehicle (ROV) is used. A Real-time data management and decision support system is in place and the water quality data are being uploaded continuously in real time in the AQUAWINGS platform where the users of the pilot can have access to them. The AQUAWINGS platform was co used in the pilot for the planning of different activities that take place in the aquaculture farm e.g., diving and feeding. Fish behaviour was continuously monitored through cameras in order to check the fish stress when diving activities were taking place.

The most important parameters monitored concerning fish aquaculture are: Dissolved oxygen, water temperature, ammonia, and of course the number of tourist divers is also of great importance.

The AQUAWINGS platform utilizes Water Quality algorithms to analyse the time series of measured parameters. This analysis aims to identify outlier values that may indicate irregularities within the system. The algorithms also calculate the probability of external events that could have caused these deviations. Automatic observations are generated, documenting these results. Moreover, trend lines and predictions for the parameters are generated, producing predicted time series. The system raises alerts for threshold violations and warnings for values approaching specified thresholds.

The Decision Support System of the AQUAWINGS platform is designed to assist operators in making informed decisions across various aspects of the operation. It is based on a set of business requirements that govern the system's logic. By leveraging the collected data, the algorithms within the system provide answers to specific user questions and offer an overview of the operational status, facilitating decision-making.

The main functionalities of the algorithms cover several aspects, including:

- Optimal feeding: Suggests the required amount of feed for each stock and automatically validates the feasibility and execution of the feeding process.
- Production planning: Provides recommendations for the timing of harvest and seeding procedures while ensuring efficient planning.
- Optimal grading: Offers feedback to operators on efficient grading scheduling, taking into account the distribution of stock inside cages to prevent large variations.
- Breeding: Allows operators to monitor fish breeding and implement efficient breeding strategies. It includes filtering fish based on specific criteria and matching healthy males to females.
- Disease prevention and mitigation: Evaluates observations and recorded environmental data to suggest actions or protocols that can prevent or mitigate specific diseases.
- Infrastructure, stock integrity, and security: Provides task planning for observed damages and suggests maintenance actions for prevention.
- Environmental footprint: Offers long-term suggestions for environmental sustainability and monitors and predicts potential violations of environmental thresholds.
- Stock welfare: Calculates indices related to Water Quality, Behaviour, Condition, Infrastructure, Husbandry, Feeding, and Environment. It evaluates all available data to provide a quantified overview of the site's status.
- Reporting: Generates reports displaying information about environmental regulatory thresholds, production status, health conditions, traceability, and ISO standards. These reports enhance the operator's decision support.

Spatial requirements

There exists no legally binding national marine spatial plan for Greece. There is therefore no overarching framework enabling or promoting MU of the seas. The relevant aquaculture site in the Greek pilot has an exploitation permit for 10 years obtained through a process which included an environmental impact assessment procedure.

This permit defines the borders of the aquaculture site. It is however unclear whether legislation allows or prohibits additional use of the same site. Though it appears to be an existing practice to notify the aquaculture company of the dive path to be used by the divers, it is unsure whether this is legally required and whether this would entail the exclusion of other users not adhering to this notification. What is more, it is unclear on what grounds the aquaculture producer may in such a case refuse access.

For the Greek pilot there is no binding National Marine Spatial Plan; no overarching policy framework. Besides, a large amount of regulation and safety standards are of potential influence, although it is not clear how that will work out, and because of that much uncertainty, in particular for the commercial exploitation. It is for example not clear whether divers could enter the area on their own initiative. These are sources of uncertainty. But on the other hand, the aquaculture site does have an exploitation permit for 10 years, based on an environmental impact assessment. The diving company also possess all the necessary certificates by Bureau Veritas and have a strong security track-record, with its own camera-based monitoring. It also has all the necessary insurances.

Logistics planning

For the Greek pilot a scheduling system has been implemented in order to plan the multi-use activities between the aquaculture unit, the touristic expeditions (and all the linked activities and scenarios between the two). Planet Blue, or KASTELORIZO can have access to the calendar and are able to check availability of the aquaculture and book a co-use activity. This scheduling tool has been created by WINGS as part of the software platform that is connected to the sensors and camera in the aquaculture site.

Accessibility

Accessibility plays a crucial role in various aspects of the aquaculture system. One important aspect is the monitoring of waste and potential pollution caused by touristic vessels. To ensure effective waste management, Planet Blue has easy access to the necessary equipment and tools, including ROVs for underwater inspections.

In terms of the societal pillar, the area aims to promote touristic growth while maintaining social acceptance of aquaculture activities. To achieve this, the area has implemented several activities that enhance accessibility. One such initiative is the inclusion of aquaculture facilities as a stop on marine tours, allowing visitors to learn about the opportunities offered by the area.

Another successful approach has been the integration of scuba diving activities with aquaculture. Moreover, Planet Blue has used ROVs to map the underwater landscape of KASTELORIZO and organize diving expeditions to explore the unique wetland created by aquaculture. These expeditions serve multiple purposes, including cleaning the aquaculture areas from waste and inspecting and repairing the infrastructure. Even infrastructure located at great depths, such as anchors, can be inspected using ROVs.

Last but not least, the Greek pilot combines fish aquaculture and diving tourism. Hence in order for someone to investigate the aquaculture site underwater the respective visitor should be a certified diver. The trainings must have six theoretical sessions, six pool water sessions and four offshore diving sessions. Except for that the staff is also trained for the use of ROVs. People with no open water diver certification are not allowed to dive in the aquaculture site. Moreover, most professional divers are required by national or state legislation to be qualified as first aid providers to a specified standard as occupational health and safety are important aspects of professional diving. For the specific pilot, no extra training was required since the divers had already been trained for underwater investigation, which also includes the site of the aquaculture farm.

Maintenance operations

Maintenance operations play a crucial role in ensuring the proper functioning and longevity of each element in the aquaculture system. Various maintenance activities are carried out to address specific needs and ensure the overall efficiency of the system.

One important aspect of maintenance is the regular cleaning of the aquaculture area from waste. Diving expeditions are conducted to remove any accumulated waste and debris that may hinder the system's performance. This cleaning process helps maintain a clean and healthy environment for the aquaculture operations. Furthermore, inspections are conducted using ROVs to assess and repair the infrastructure. The aquaculture diver is equipped with an ROV to conduct inspections while underwater, allowing for close examination of the system's components. This helps identify any potential issues or damages that may require immediate attention.

Additionally, inspections using ROVs are carried out for aquaculture infrastructure located in great depths, such as anchors. These inspections provide valuable information about the condition of the anchorage system, ensuring its stability and reliability. The positive results obtained from these underwater inspections and photographs confirm that the maintenance expeditions are safe for the divers, indicating that the system is well-maintained.

The impact of maintenance on design procedures is significant. By conducting regular cleaning expeditions and inspections, potential issues and maintenance requirements can be identified and addressed promptly. This proactive approach to maintenance helps optimize the design procedures by improving the overall reliability and performance of the aquaculture system.

Design procedure limitations and improvements

Limitations of current design procedures:

- Weather-dependent diving tours: Diving expeditions are subject to cancellation if weather conditions exceed safety limits, such as wind speed exceeding 4 Beaufort or strong currents. While these measures ensure safety, they can lead to cancelled dives and potential customer dissatisfaction.

- Limited dive site options: The availability of dive sites depends on weather conditions. There are a total of 55 dive sites, but the choice is restricted based on weather suitability. This limitation may impact divers' options and experiences.
- COVID-19 restrictions: The measures against the COVID-19 pandemic had resulted in the cancellation of many dives and the restriction of group sizes. Smaller group sizes and stringent safety protocols led to limitation of the number of dives and participants.
- Qualification and experience requirements: Divers with limited or medium experience or those who haven't dived in the past year are required to take a "refresh-test" dive accompanied by an instructor before the planned dive. While this ensures safety, it adds extra steps and may restrict some divers' ability to participate immediately.

Possibilities for improvements in design procedures:

- Enhanced weather monitoring and prediction: Improving the accuracy and timeliness of weather forecasts can help in better planning and reducing the number of cancelled dives. Access to real-time weather data and advanced forecasting techniques can aid in making more informed decisions.
- Diversification of dive sites: Expanding the range of dive sites or exploring alternative options for diving locations can provide more choices to divers and accommodate various skill levels and preferences. This can enhance the overall diving experience.

Synergies between different MUCL elements:

The diving operations and aquaculture activities can potentially benefit from synergies, leading to mutually advantageous outcomes. For example:

- Cleaning of aquaculture areas: Diving expeditions can be utilized not only for recreational purposes but also for cleaning the aquaculture areas from waste and debris. This synergy promotes a cleaner environment for aquaculture operations while enhancing the diving experience through participation in conservation efforts.
- Inspection of aquaculture infrastructure: The use of ROVs during diving expeditions allows for the inspection of both the diving infrastructure and the aquaculture facilities. This integrated approach ensures the regular monitoring and maintenance of both elements, contributing to the overall efficiency and safety of the operations.
- Promotion of eco-tourism: By incorporating aquaculture facilities as part of the diving tour, it provides an opportunity to educate and raise awareness among tourists about the importance of sustainable aquaculture practices. This synergy promotes eco-tourism and supports social acceptance of aquaculture activities in the area.

Exploring and further developing these synergies can lead to a more integrated and sustainable approach to both diving operations and aquaculture activities, enhancing the overall experience and benefits for all stakeholders involved.

6.2. Benefits, risks and limitations

The Greek pilot, a dynamic integration of aquaculture and tourism activities, introduces a range of environmental monitoring, technological infrastructure, and scheduling mechanisms to facilitate multi-use in the marine environment. Based on the above information and on UNITED D7.4 (2022), D7.5 (2023) the benefits and synergies are being described below:

Benefits

Real-time Environmental Monitoring

The Greek pilot stands out for its comprehensive real-time monitoring of aquaculture production parameters. Parameters such as salinity, water quality, temperature, dissolved oxygen, and fish behaviour are continually assessed using advanced technologies like underwater sensors and cameras. This data feeds into the AQUAWINGS platform, providing users with immediate access to vital information. The integration of meteorological sensors also contributes to a holistic understanding of environmental conditions.

Decision Support System for Operational Excellence

The AQUAWINGS platform incorporates a robust Decision Support System that aids operators in making informed decisions across various facets of aquaculture operations. This system utilizes algorithms for optimal feeding, production planning, grading, breeding, disease prevention, and more. The platform's predictive capabilities enhance the efficiency and sustainability of aquaculture activities, contributing to optimal stock welfare and infrastructure integrity.

Multi-use Scheduling System

To ensure effective coordination between aquaculture and tourism activities, a scheduling system has been implemented. This system allows external entities, such as Planet Blue or KASTELORIZO, to access the calendar, check aquaculture availability, and book co-use activities. This approach streamlines logistics and promotes a collaborative environment.

Enhanced Accessibility and Societal Integration

The Greek pilot promotes accessibility through initiatives like including aquaculture facilities as stops on marine tours. Scuba diving activities are integrated with aquaculture, and underwater inspections are facilitated by ROVs, allowing for effective waste management and infrastructure monitoring. These activities enhance societal acceptance by offering educational opportunities and contributing to the growth of eco-tourism.

Risks

Weather-Dependent Operations

One notable risk in the Greek pilot is the dependence on weather conditions for diving tours. Safety measures dictate cancellations in the face of adverse weather, potentially leading to dissatisfaction among customers. The unpredictability of weather patterns poses a continuous challenge for planning and executing diving expeditions.

Qualification and Experience Requirements

Participants in underwater investigations of the aquaculture site must be certified divers, adding a layer of qualification requirements. While ensuring safety, this prerequisite may limit the pool of potential visitors. Moreover, divers with limited experience may need additional training, affecting their immediate participation.

Limitations

Legally Ambiguous Marine Spatial Planning

The absence of a legally binding national marine spatial plan for Greece introduces uncertainties regarding the permissibility of additional uses of the aquaculture site. Legal clarity on notification requirements and grounds for refusal of access is lacking, posing challenges for co-use scenarios.

Weather-Dependent Diving Tours

Weather conditions not only impact safety but also lead to the cancellation of diving tours, affecting the overall accessibility of the aquaculture site. The unpredictability of weather patterns remains a significant limitation in designing consistent and year-round tourism activities.

Logistical Challenges and Resource Dependence

Coordinating schedules, managing equipment availability, and depending on external resources, such as ROVs, introduce logistical challenges. These challenges may impact the efficiency and frequency of maintenance operations, requiring careful planning and coordination to overcome. Accessibility and logistics can pose challenges, particularly when conducting inspections in deep-sea locations. Coordinating diving expeditions, ensuring the availability of ROVs, and managing the logistics of equipment and personnel can be complex and time-consuming. These limitations may impact the efficiency and frequency of maintenance operations, requiring careful planning and coordination to overcome them.

7. SIMILARITIES OF BENEFITS, LIMITATIONS AND RISKS BETWEEN PILOTS

In exploring the Multi-Use platforms (MUCL) initiatives across Germany, Belgium, the Netherlands, Denmark, and Greece, each pilot uniquely integrates aquaculture with various activities. Despite differences in regional approaches, there are shared challenges and opportunities.

These MUCL pilots represent innovative efforts to integrate aquaculture operations with different elements, ranging from offshore wind and solar energy to tourism. An analysis of the similarities among the pilots follows.

Shared Benefits

Real-time Environmental Monitoring: All pilots emphasize continuous environmental monitoring, utilizing advanced technologies to understand and improve operational efficiency.

Multi-use Scheduling: Universal adoption of scheduling systems facilitates effective coordination between aquaculture and related activities, supporting a collaborative environment.

Shared Limitations

Weather-Dependent Operations: Challenges arising from weather-dependent operations impact aquaculture activities in all pilots, affecting overall accessibility.

Qualification and Experience Requirements: Universal limitations include qualification requirements for visitors, such as the need for certified divers, potentially restricting the pool of participants.

Legally Ambiguous Framework: Legal uncertainties in marine spatial planning are noted across pilots, introducing challenges regarding additional uses of aquaculture sites.

Shared Risks

Weather-Dependent Operations: Risks associated with cancellations due to adverse weather conditions are universally shared, impacting the reliability of operations.

COVID-19 Impact: COVID-19 restrictions posed risks, affecting the number of activities and participants in all pilots.

Logistical Challenges: Coordinating schedules and depending on external resources introduce logistical challenges, emphasizing the need for careful planning.

8. RECOMMENDATIONS

Recommendations for future research and development in MUCL engineering

Research and development can be shaped by a set of forward-looking recommendations in the ever-evolving field of MUCL. These recommendations cover technical innovation, interdisciplinary cooperation, legal frameworks, community involvement, and adaptive management. Creating integrated coastal activities that are resilient, sustainable, and socially acceptable requires embracing these factors.

Engineering Standards and Protocols: Establish standardized engineering protocols for the design, construction, and maintenance of multi-use coastal structures. This could include guidelines for integrating aquaculture facilities, tourism infrastructure, and other activities into a cohesive engineering framework.

Innovative Structural Designs: Encourage research into innovative structural designs that are specifically tailored for multi-use applications. This involves developing engineering solutions that accommodate the diverse needs of aquaculture, tourism, and other coastal activities.

Adaptive Engineering Approaches: Implement adaptive engineering approaches that allow for flexible and modular designs. This ensures that coastal structures can adapt to changing environmental conditions, different uses, and emerging engineering technologies.

Integration of Renewable Energy: Explore the integration of renewable energy systems into multi-use coastal structures. This involves incorporating technologies such as solar panels, wind turbines, or wave energy converters to enhance sustainability and reduce reliance on traditional energy sources.

Efficient Resource Utilization: Focus on engineering solutions that optimize the utilization of resources, including space, water, and energy. Efficient resource management is critical for ensuring the economic viability and sustainability of multi-use coastal projects.

Environmental Impact Mitigation: Develop engineering strategies to mitigate the environmental impact of multi-use coastal structures. This may include designs that minimize habitat disturbance, prevent pollution, and promote the overall health of marine ecosystems.

Technological Integration for Monitoring: Integrate advanced technologies for real-time monitoring and data collection. This involves incorporating sensors, IoT devices, and other monitoring tools into the engineering design to provide insights into the performance and environmental impact of the coastal structures.

Safety and Risk Mitigation Measures: Prioritize the integration of safety features and risk mitigation measures in the engineering design. This includes structural resilience to extreme weather events, safety protocols for aquaculture and tourism activities, and emergency response plans.

Life Cycle Analysis: Conduct life cycle analyses for multi-use coastal structures to assess their long-term environmental and economic impacts. This involves evaluating the sustainability of materials, energy consumption, and the overall ecological footprint of the engineering project.

Collaboration with Industry Experts: Foster collaboration between engineers and industry experts in aquaculture, tourism, and related fields. This collaborative approach ensures that engineering solutions align with the specific needs and operational requirements of each industry involved in multi-use coastal activities.

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