Environmental Monitoring Plans (EMP) conceptual framework for Mariparks

Deliverable 4.6

2026

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Contents

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List of acronyms

ADCP	Acoustic Doppler Current Profiler
AIS/VMS	Automatic Identification System/Vessel Monitoring System
AUV	Autonomous Underwater Vessel
CIA	Cumulative Impact Assessment
CMEMS	Copernicus Marine Environment Monitoring Service
CTD	Conductivity, Temperature, Depth
D	Deliverable
DestinE	Destination Earth
DH	Data Hub
DO	Dissolved Oxygen
DTO	Digital Twin of the Ocean
EBA	Ecosystem-Based Approach
EBM	Ecosystem-Based Management
EBS	Environmental Baseline Study
eDNA	Environmental DNA
EDITO	European Digital Twin of the Ocean
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
EMP	Environmental Management Plan
GNSBI	Greater North Sea Basin Initiative
HAB	Harmful Algae Bloom
HPC	High-Performance Computing
INSPIRE	Infrastructure for Spatial Information in Europe
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LTA	Low Trophic Aquaculture
MSFD	Marine Strategy Framework Directives
MSP	Marine Spatial Planning
MSPdF	Marine Spatial Planning Decision Framework
MU	Multi-Use
N	Nitrogen
OPV	Offshore Photovoltaic
ORE	Offshore Renewable Energy
OWF	Offshore Wind Farm
P	Phosphorus
PAM	Passive Acoustic Monitoring
PAR	Photosynthetically Active Radiation
QA/QC	Quality Assurance/Quality Control
ROV	Remotely operated vehicle

SDI	Spatial Data Infrastructure
SEA	Strategic Environmental Assessment
Si	Silicon
SM	Smart Monitoring
SSP	Shares Socioeconomic Pathways (Climate scenario's)
SST	Sea Surface Temperature
TOC	Total Organic Carbon
UNITED	H2020 Project on Multi-Use Offshore Platforms (2020-2023)
ULTFARMS	Horizon Project on Ultra-Large Offshore Farms (2023-2026)
WP	Work Package

Executive Summary

This deliverable (D4.6) proposes a conceptual framework for Environmental Monitoring Plans (EMP) tailored to Mariparks. Mariparks are emerging Multi-Use (MU) offshore areas combining renewable energy (offshore wind, floating photovoltaics), aquaculture, nature restoration, and advanced monitoring systems. Unlike traditional EMPs designed for single sectors, Mariparks require an ecosystem-based, integrated approach to manage cumulative impacts and and to evaluate whether environmental sustainability objectives, including the ambition of net positive ecological impact, can be met under specific configurations and conditions.

The framework introduces three pillars:

- (i) Smart monitoring systems for continuous and autonomous data acquisition,
- (ii) A centralized Data Hub for governance, standardization, and interoperability,
- (iii) Digital Twin components that strengthen real-time analysis, cumulative impact assessment, and scenario-based decision-making.

The EMP is structured in a systematic step-by-step approach, composed of eight steps: scoping, initialization, indicator and protocol definition, data collection and standardization, integration and mapping, compliance checks, adaptive monitoring, and synthesis and reporting. Each step is designed to support interoperability of systems, transparency of data, and climate resilience, ensuring that monitoring evolves with technological maturity and operational complexity. Lessons learned from European MU pilots such as UNITED and ULTFARMS highlight the importance of prioritizing robustness over complexity, establishing clear governance and data-sharing protocols, and integrating ecological and operational indicators to capture cumulative pressures and interactions between co-located activities. Together, these components provide the basis to assess progress towards the net positive ecological impact ambition of Mariparks.

The report also explores the articulation between Mariparks EMPs and EDITO, the European Digital Twin of the Ocean, to enable basin-level coordination, cumulative impact assessment, and strategic environmental planning. The recommendations emphasise the need to build on existing regulatory frameworks, investing first in governance and interoperability, deploying advanced technologies progressively, and embedding climate resilience from the outset.

The proposed EMP framework is conceptual yet operationally oriented, modular, scalable across different maturity levels of Mariparks, and designed to evolve from mono-use sites to fully integrated multi-use systems. By combining data-driven monitoring, adaptive management, and future-oriented digital tools, this framework provides a transferable model for environmentally responsible development of Ocean MU infrastructures across European sea basins.

Introduction

Deliverable D4.6 builds on the work undertaken in D4.3 and advances the objectives of Work Package 4 (WP4), which aims to develop an integrated approach to environmental planning, monitoring and management for Mariparks, and in particular capitalises on lessons learnt from recent European MU pilot projects such as UNITED and ULTFARMS. D4.3 defined the structure and methodological requirements for a harmonised Environmental Baseline Study (EBS), placing data governance at the core of the monitoring strategy. The results of D4.3 demonstrated the need for a coordinated and adaptive Environmental Management Plan (EMP) to guide operations throughout the lifecycle of a Maripark. D4.6 responds to this need.

The Maripark tool [1] is defined as a flexible and future-proof Multi-Use (MU) offshore system, capable of integrating a range of activities supported by advanced technologies and integrated governance models, in response to societal needs and with the ambition of achieving a net positive ecological impact. This concept is intentionally broad and not limited to specific technological or sectoral configurations.

In this deliverable, the EMP framework is illustrated through a set of most probable multi-use scenarios identified in Task 4.4, combining renewable energy production (e.g. offshore wind farms (OWF) and offshore photovoltaic (OPV) systems), aquaculture activities, nature restoration functions and advanced monitoring systems. While these scenarios provide a concrete reference for the application of the EMP, they do not constrain the broader Maripark concept.

Unlike traditional EMPs, which are typically designed for single-sector developments, the complexity arising from the co-location of multiple uses requires a holistic and systematic approach grounded in an ecosystem-based perspective.

The proposed framework adopts Ecosystem-Based Management (EBM) principles, emphasizing the interconnectedness of ecological compartments, multi-sector interactions, and cumulative effects [2] [3]. It aligns with EU directives promoting ecosystem-based approaches such as Marine Spatial Planning Directive (MSPD 2014/89/EU) [4], the Marine Strategy Framework Directive (MSFD, 2008/56/EC) [5], and recent frameworks on offshore renewable energy sustainability [6].

The EMP is structured to follow the technological and operational evolution of Mariparks, as defined in Task 4.4:

Phases	Cases
Phase_0	Mono-use: existing single-use offshore sites
Phase_1	Pilot MU: experimental co-location of uses (aquaculture, OPV) within existing OWF
Phase_2	Integrated Mariparks: full-scale MU sites

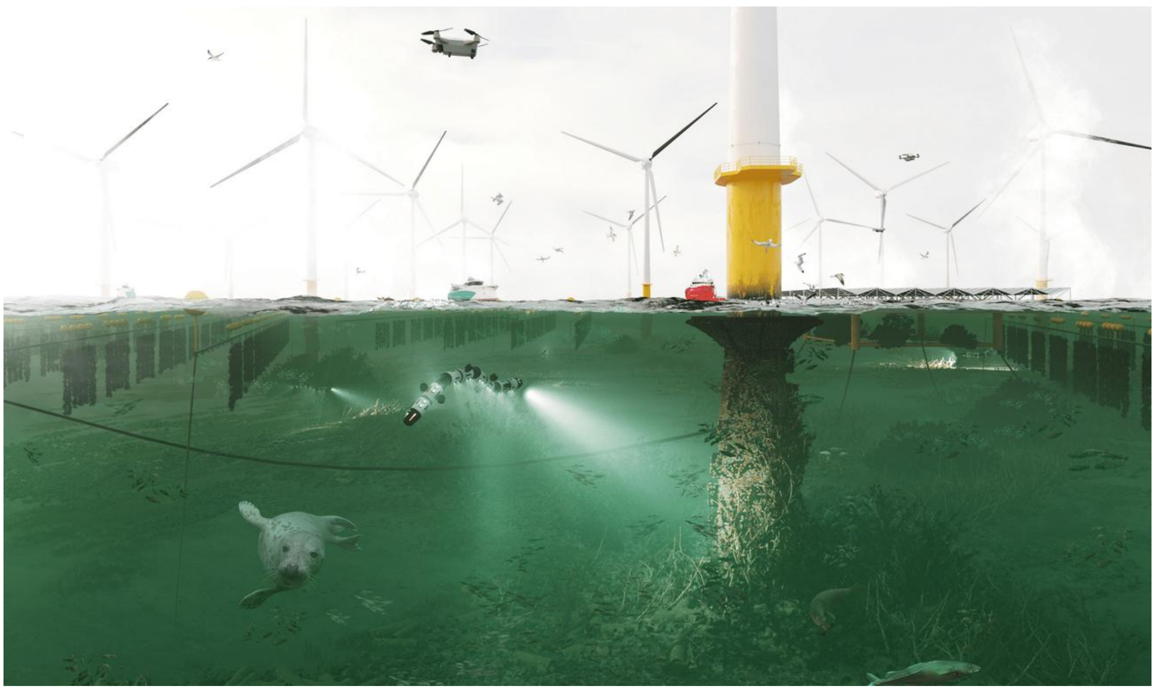

Figure 1: Phase 1 of Mariparks [7]

These phases correspond to progressive integration of technologies, governance, and data systems. The EMP ensures environmental protection and sustainable MU operations throughout this evolution. A Maripark hub gradually emerges as a combined operational and data-management center, integrating smart monitoring, a shared Data Hub (DH) and, at higher maturity levels, interaction with Digital Twin of the Ocean (DTO) tools to support interoperable and adaptive management across sectors.

The objectives of D4.6, designed for public authorities and Mariparks developers, are to:

- Provide a conceptual EMP framework tailored to Mariparks,
- Support adaptive, long-term, data-driven EBM,
- Clarify how smart monitoring, DH and DTO components can be integrated within the EMP cycle,
- Explore articulation between Mariparks and EDITO: data flows and complementary roles

Given that Mariparks are long-term infrastructures expected to operate potentially over several decades, the EMP explicitly integrates future-oriented environmental data and climate projections, building upon the data framework established in D4.3.

This deliverable does not aim to assess the technical feasibility of all monitoring technologies, but to provide a conceptual and structured framework within which such technologies can be progressively integrated.

This report focuses on environmental approaches to ensure consistency with D4.3. The frameworks for socio-economic aspects, governance and Ecosystem-Based Approach (EBA) management will be further developed under T4.1 and T4.2, while T4.5 will address upscaling and basin-level applications. The report also acknowledges that current EMP practices in offshore wind, aquaculture, and MSP often lack integration, interoperability, and real-time responsiveness. D4.6 therefore proposes an actionable framework that links baseline assessment, monitoring, data governance and adaptive management, supported by data standardisation, cybersecurity considerations and interoperability requirements. This provides a foundation for the environmentally responsible development and operation of future Mariparks.

Within, this context, T4.4 focused on the development of Maripark scenarios, exploring different combinations of activities and assessing their economic and political feasibility and their temporality. Building on these scenario-based foundations, Deliverable D4.6 develops a conceptual EMP framework, scalable and modular, providing the scientific and environmental reference needed to assess the ecological implications of such configurations. Initial deployments should prioritise robustness, reliability and maintainability over full system integration, which can be achieved progressively as capacities mature following phase defined in T4.4.

This work also aligns with the objectives outlined in the European Ocean Pact, particularly regarding the development of integrated monitoring, data sharing and smart systems to support sustainable ocean management and informed decision-making.

Figure 2: Schematic representation of potential Mariparks combination [7]

I. From environmental baseline to management plan

This part outlines how the EBS developed in D4.3 directly informs and transitions into the monitoring framework of the EMP for an integrated Maripark. The EMP must therefore address cumulative effects between renewable energy systems, aquaculture operations, OPV structures, nature restoration functions, and associated maritime logistics. Data must be interoperable across operators and monitoring platforms to enable joint assessment, shared decision-making, and efficient environmental protection across the whole MU site.

1.1. Role of the EBS

The EBS, defined in D4.3, provides the reference for environmental conditions prior to the development of a Maripark. It establishes a harmonized and interoperable dataset describing the state of the ecosystem at a given point in time, including abiotic components, ecological communities, existing pressures, and spatial designations. Such baseline information is essential for predicting impacts, defining monitoring needs, and designing mitigation measures in line with the EBA.

D4.3 placed a strong emphasis on:

- Data harmonization,
- Multi-source integration,
- Quality assurance,
- And interoperability across sectors and operators.

They are strongly integrated through the EBS framework proposed (Figure 3). This data-centralized approach forms the backbone of the transition from EBS to EMP.

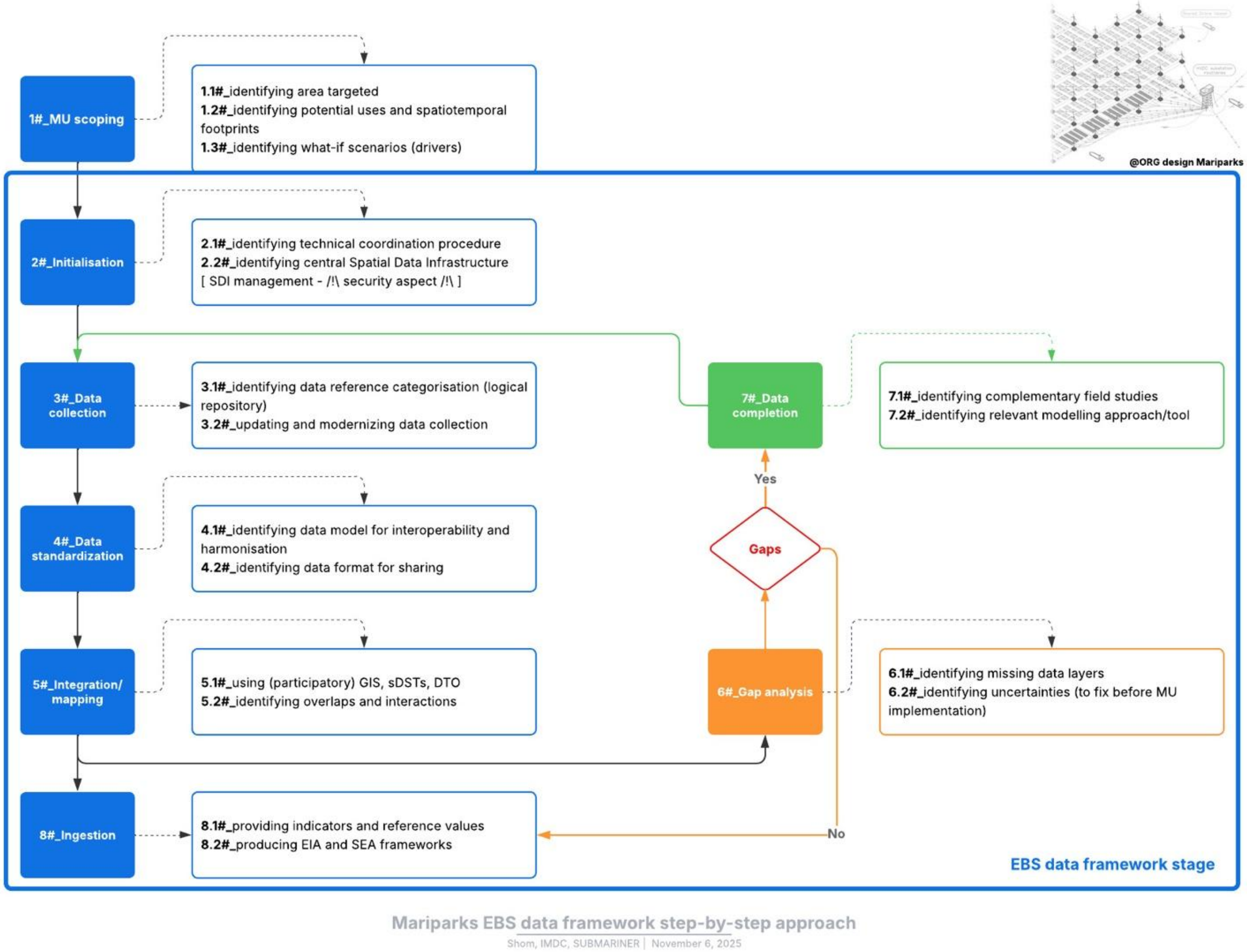

Figure 3: Mariparks EBS data framework step by step approach [1]

1.2. EBS informs EIA

Before installation of Maripark components, the baseline supports the Environmental Impact Assessment (EIA) process, which identifies potential pressures and cumulative impacts arising from activities defined in T4.4:

- Offshore wind and OPV systems,
- Aquaculture structures,
- Nature restoration activities,
- Logistics and maritime operations,

- Potential military or surveillance co-use,
- And other optional future functionalities (e.g., offshore hydrogen or desalination units).

The consideration of potential military or surveillance co-use highlights the need to address safety, access and data-related constraints early in the design phase, in line with a security-by-design approach.

The EIA uses baseline data to:

- Predict changes to ecosystem components (habitats, species, hydrography),
- Identify vulnerabilities and thresholds that require monitoring,
- Define mitigation and enhancement measures,
- Specify post-construction monitoring obligations.

The combination of a harmonized EBS and a site-specific EIA forms the evidence base on which the EMP is constructed. A key difference with traditional EIAs is that cumulative impacts arise not only from each activity individually, but from their interactions within a confined spatial footprint. This specificity requires advanced monitoring technologies, integrated modelling, and a centralized Data Hub to manage multi-operator data flows, initiated already for the EBS stage, as highlighted in D4.3.

1.3. The EMP: purpose and structure

Once the Maripark is operational, a long-term monitoring system becomes mandatory under EU environmental legislation (EIA Directive, MSFD, Birds and Habitats Directives…), and essential for adaptive EBM.

An EMP translates regulatory requirements, project-specific objectives, and baseline findings into operational monitoring and management procedures. The EMP's main objectives are to:

- Ensure ecological protection during the Maripark lifecycle,
- Detect and evaluate environmental changes relative to the baseline,
- Verify the effectiveness of mitigation and enhancement measures,

- Support adaptive management and scenario-based decision making,
- Ensure transparent, interoperable, and secure data-sharing with public authorities,
- Meet national permitting and EU reporting obligations.

The EMP supports the Ecosystem-Based Approach (EBA). Implementing an EBA means that the planning, operation, and monitoring of the Maripark are guided by an integrated understanding of the entire marine ecosystem, its species, habitats, ecological processes, and human uses, rather than focusing on individual activities in isolation.

EBA recognizes that offshore wind, solar installations, aquaculture, shipping, fisheries, and military uses all interact within the same marine space. The goal is to balance ecological integrity, economic benefits, and societal needs while maintaining the long-term health and resilience of the marine environment.

In the context of the Maripark and its digital twin, EBA means:

- Holistic integration: environmental, operational, and security data are analysed together to understand cumulative impacts, ecosystem responses, and cross-sector interactions.
- Precautionary and adaptive management: the digital twin supports real-time monitoring, early-warning systems, and predictive modelling so that management actions can be adjusted proactively as conditions change.
- Maintaining ecological function and respecting carrying capacities: activities such as aquaculture, energy production, logistics, and surveillance are designed and operated in ways that preserve key ecosystem processes, biodiversity, and habitat quality.
- Cumulative impact understanding: The digital twin enables simulation of combined pressures: noise, nutrient inputs, habitat disturbance, vessel traffic, and supports decision-making to minimise negative cumulative effects.
- Cross-sector coordination: the central hub facilitates cooperation between energy operators, aquaculture managers, environmental authorities, and military or asset-protection stakeholders.
- Socio-ecological balance: decisions consider ecological impacts alongside social and economic objectives, ensuring long-term sustainable use of the marine area.

- Evidence-based decisions: continuous data flows feed into the digital twin, creating a science-based foundation for evaluating management options and forecasting future ecosystem states.

The importance of adopting a harmonized, multi-sector monitoring approach has been highlighted in multiple European studies. For example, OSPAR Commission [8] stresses the need for regional coordination in monitoring programs, particularly regarding underwater noise, contaminants, and biodiversity. Research from offshore wind environments [6] demonstrates that shared monitoring frameworks lead to improved cumulative impact assessments and more coherent regional decision-making. The Maripark EMP framework incorporates these lessons by proposing integrated indicator sets, standardized protocols, and adaptive management loops responsive to newly acquired data and emerging risks.

The Maripark EMP adopts a long-term perspective aligned with the expected operational lifespan of offshore infrastructures, ensuring that environmental performance is assessed not only against current conditions but also in relation to projected future environmental states as highlighted in D4.3 [1].

Rather than following a generic, activity-based EMP structure, the Maripark EMP is conceived as a data-driven, adaptive framework explicitly designed for ocean MU. Its operational structure is therefore developed in detail in Section III.

1.4. A shared data architecture across EBS, EIA and EMP

D4.3 demonstrated that a Maripark cannot operate effectively without a coordinated data architecture.

Data cycles (data collection/ standardisation/integration/ mapping) recur at three key moments of the Maripark development process. This continuity ensures that environmental management remains aligned with changing conditions, emerging pressures, and technological developments.

The shared data architecture must support multi-operator data flows and merged environmental and operational datasets. This is specific to the Maripark concept and will be the backbone of our Maripark EMP framework proposal (see more in section II dedicated to Data Hub, smart monitoring and Digital Twins and in the initialisation phase section III).

Cycle order	Step	Data description
1st cycle	EBS	Compilation and harmonisation of existing datasets to describe pre-project environmental conditions and addition of complementary data from field studies when needed.
2nd cycle	EIA	Use the baseline to model impacts and identify monitoring requirements and thresholds.
3rd cycle	EMP	Continuous monitoring, analysis, and update of environmental data throughout the lifecycle of the Maripark, supported by repeated loops of: • field measurements, • smart monitoring technologies, • model simulations, • impact evaluation.

Table 1: Mariparks' cycles from EBS to EMP

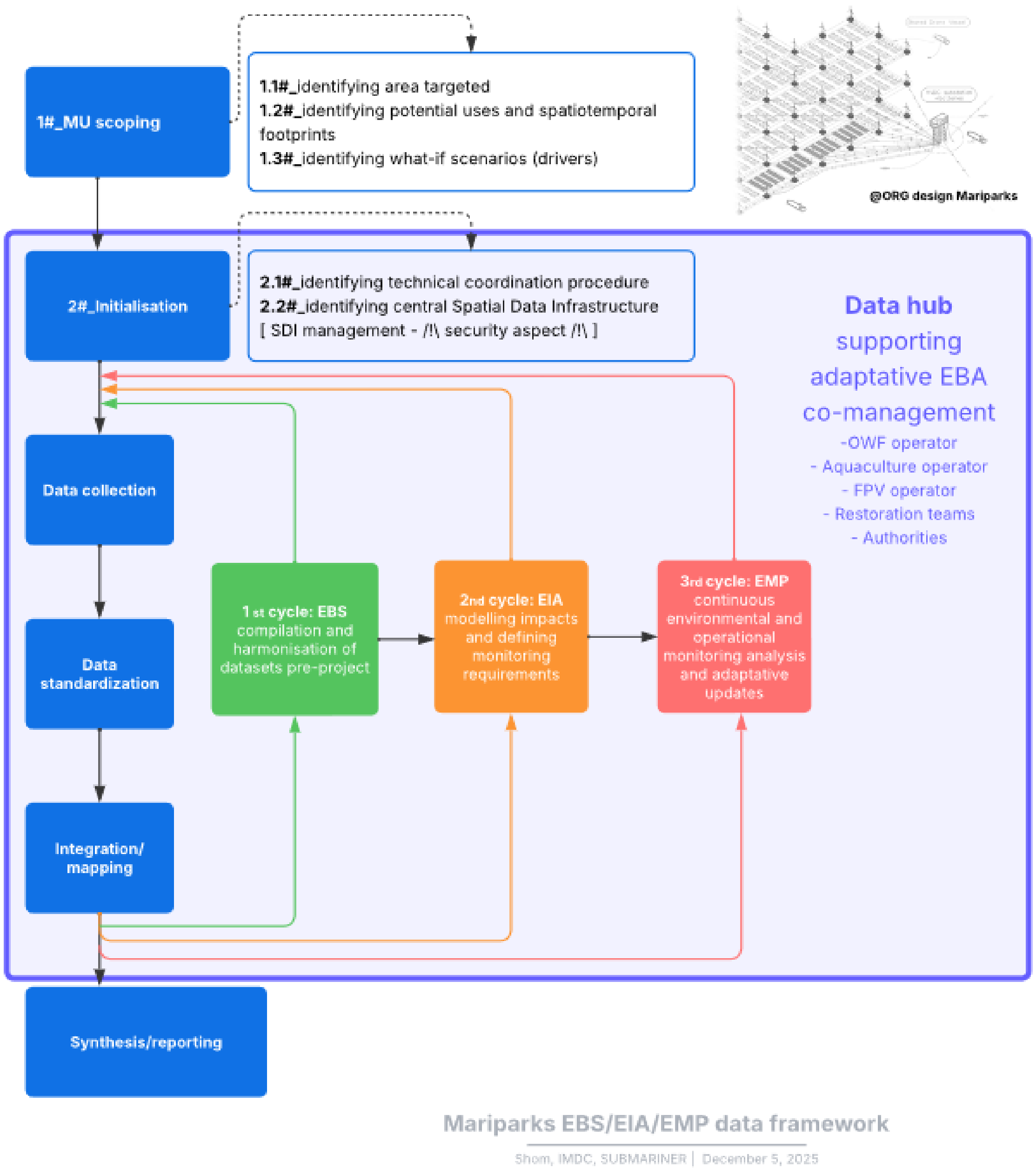

Figure 4: Mariparks EBS/EIA/EMP data framework

1.5. Position of the EMP within the Maripark framework

Building on the shared architecture developed in D4.3, the EMP framework focuses on the implementation of environmental monitoring and adaptive management within Mariparks.

This framework will be operational for all phases of WP4, and adaptation will be discussed in the conclusion. By embedding EBA within the Maripark monitoring and data architecture, including Digital Twin tools, where available, the Data Hub evolves beyond an operational system into a platform for environmental intelligence, supporting informed multi-use management over the long term.

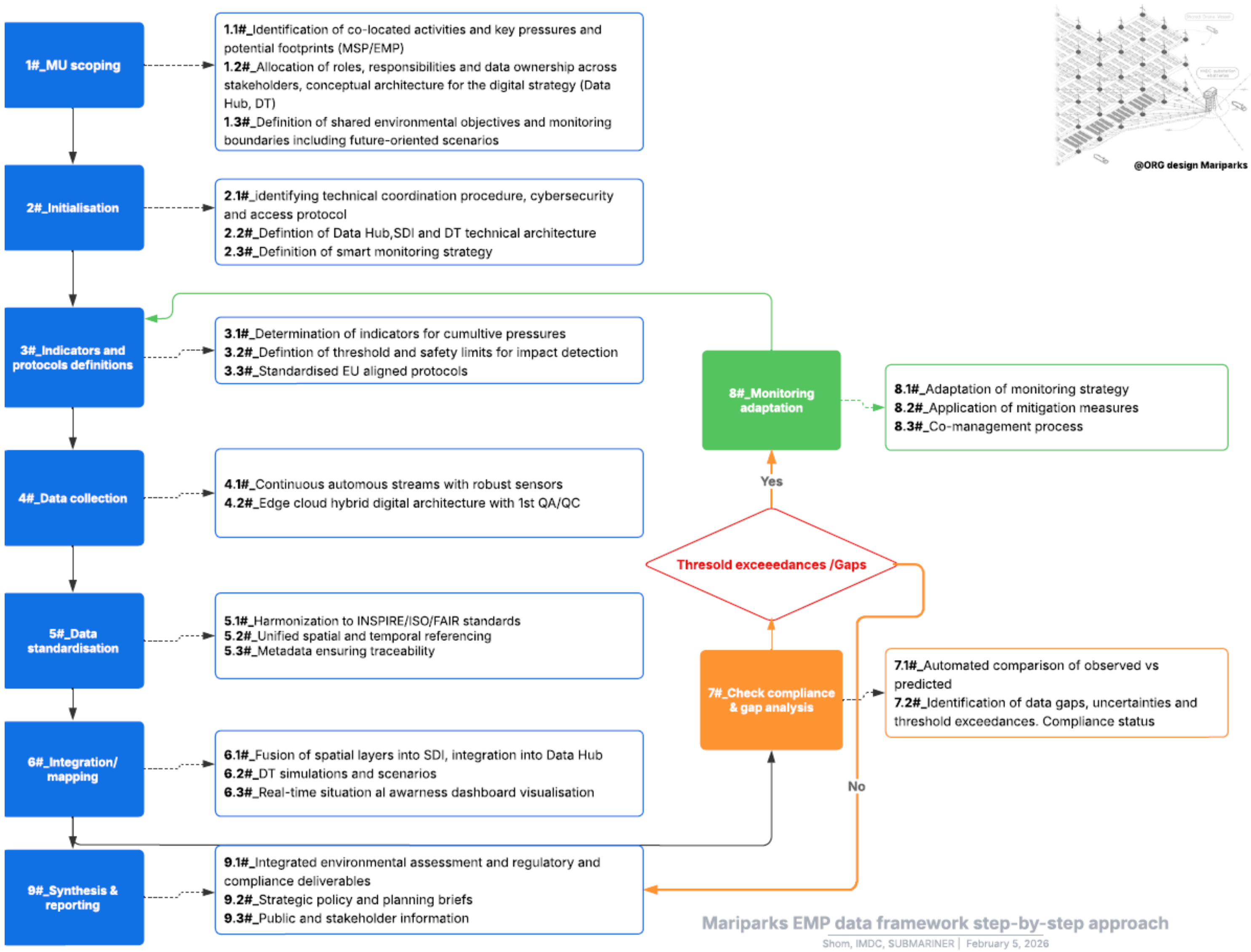

Figure 5: Mariparks EMP data framework step-by-step approach

1.6. Lessons learned from MU pilots

Experience from recent MU pilots from EU projects, specifically ULTFARMS (Horizon Project on Ultra-Large Offshore Farms) and UNITED (H2020 Project on Multi-Use Offshore Platforms), focusing on OWF and aquaculture co-location, provides critical insights for the design of EMP in Mariparks.

An exhaustive analysis of these pilots is presented in Annex 1, while the key lessons directly relevant to the EMP framework are synthesised below.

Lessons learned	Context & explanation	Impact on the Maripark EMPs framework
Robustness over complexity	Harsh offshore environments (as evidenced in ULTFARMS) can prevent access for weeks. High-precision sensors are useless if they fail due to lack of robustness.	Defines the selection criteria for autonomous systems and sensors in Section II.1 Smart Monitoring.
MU-specific integrated indicators	In MU settings, environmental impacts and operational risks (e.g., gear tension, cable proximity) are coupled and must be monitored together.	Directly influences the selection of cross-sectoral indicators in Section III.3 Indicators & Protocols.
Clear governance & responsibility	UNITED highlighted that a lack of clear delineation between operators and authorities leads to response paralysis during incidents.	Shapes the data-sharing protocols and access rights defined in the Data Hub II.2.
Operational synergies in alert systems	Using the same sensor network for both food safety (HABs) and ecological health (water quality) reduce costs and increases responsiveness.	Feeds into the early warning systems functions of the Digital Twin (II.3) and the adaptation loop in III.8.
Strategic value of biomass accounting	Monitoring nutrient and carbon sequestration (aquaculture/seaweed) adds significant weight to licensing and nature-inclusive design.	Can be integrated as a specific modelling output within the Digital Twin (II.3) for ecosystem services valuation.

Table 2: Lessons learned from UNITED and ULTFARMS

Governance aspects, including roles, responsibilities and data ownership, are addressed in Task 4.1. Within this framework, the EMP highlights the critical importance of clear data stewardship arrangements as a prerequisite for effective monitoring and decision-making.

Based on the governance selection, monitoring principles and the lessons learned defined in Section I, Section II presents the digital and technical backbone of the EMP. It details how a three-pillar architecture: smart monitoring systems, a centralised Data Hub, and, where relevant, Digital Twin tools, enables the operational implementation of ecosystem-based, multi-use, and long-term environmental monitoring in Mariparks.

II. Smart monitoring, Data Hub and DTO: the technological backbone of the EMP framework

The transition from a harmonised EBS to an operational EMP requires a monitoring system able to continuously capture environmental, operational, and ecological changes in a complex multi-use offshore environment and aggregate data from *in situ* sensors, satellite imagery, biological surveys, AIS/VMS vessel tracking, and operational system logs.

Mariparks, phase 1 and mostly for phase 2, will operate as digitally enabled offshore infrastructures, thanks to DTO, where real-time observations, automated systems, advanced modelling, and secure data integration converge to support adaptive, ecosystem-based management. The deployment of full DTO capabilities remains a medium to long-term perspective, dependent on data availability, technological maturity and governance alignment. In the short term, partial or modular implementations are more realistic.

The environmental footprint of monitoring technologies themselves (e.g. energy consumption, materials, maintenance) should be considered within the Ecosystem-Based Approach to ensure that the Mariparks will remains with a net positive impact. This part will be studied in T4.1.

This section describes how smart monitoring technologies, the Maripark data hub, and DTO components interact to form the robust technological backbone of the proposed EMP framework.

2.1. Smart monitoring: optimizing MU data acquisition

Smart data management refers to an integrated, technology-driven approach for collecting, storing, processing, analysing, and sharing data in a way that maximises its value for operational, environmental, and security decision-making. Smart monitoring offers continuous, high-resolution, and often real-time data streams. It includes technological components and an edge-cloud architecture to be efficient.

Technological components to module in function of the needs:

Component	Functions
IoT and static sensors	Continuous measurement of water quality (temperature, salinity, oxygen), hydrography, turbidity, underwater noise, structural loads, and early detection of Harmful Algal Blooms (HABs).
Autonomous systems	These systems include Autonomous surface and Underwater Vehicles (AUVs), gliders, smart moorings, eDNA samplers, and AI-assisted imaging platforms [9] [10]. They allow partially extensive biodiversity surveys, benthic and pelagic habitat mapping, high-resolution hydrographic monitoring, and inspection of submerged structures.
Aerial and underwater drones	Rapid inspection of surface and subsurface infrastructure, wildlife observations (birds, mammals), detection of surface pollution or debris, structural surveillance, and support during extreme events.
Remote sensing (satellite optical, thermal, SAR)	Remote sensing and satellite-derived information form another essential pillar of data collection. Multispectral, hyperspectral, and radar imagery from platforms like Sentinel-1, Sentinel-2, and Sentinel-3 provide large-scale observations of chlorophyll-*a*, turbidity, ocean colour, surface temperature, vessel traffic, and coastline or habitat changes [11]. High-resolution commercial satellites can complement these datasets by providing fine-scale imagery needed for habitat mapping or infrastructure inspections.
Operational data streams	Integration of turbine performance logs, floating PV telemetry, aquaculture gear integrity data, and AIS/VMS vessel traffic for combined environmental–operational situational awareness.
Event-detection systems	Automated alerts for drifting or damaged gear, vessel intrusion, cable proximity risks, extreme weather events, and HAB-related hazards to operations and ecosystems.

Table 3: Potential smart monitoring technological components and functions

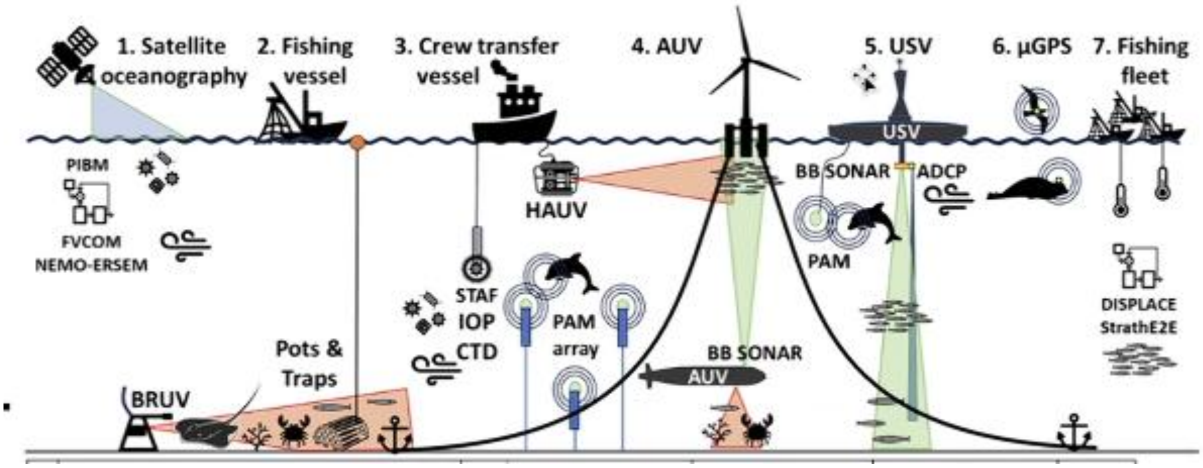

Figure 6: Potential Mariparks EMP smart monitoring devices (Heriot Watt University, 2025)

The edge cloud architecture:

Smart monitoring relies on a hybrid digital architecture:

- Edge computing filters data loads and performs first-level QA/QC at sea. It is the on-site processing of raw data directly at the source to enable real-time filtering, analysis, and event detection before transmission to the Data Hub; it allows deletion or correction of erroneous data or sensor deficiencies,
- Cloud environments handle large-scale analytics, archive storage, and machine learning,
- Secure communication pathways enable multi-operator data exchange.

In MU context smart monitoring enables:

- Continuous observation despite difficult access,
- Integration of environmental and operational parameters,
- Rapid detection of multi-use interaction risks,
- Potential cost reductions through automation (studied in T4.2),
- Support for rigorous, data-rich cumulative impact assessments, made implementable through the Data Hub's standardisation and fusion capabilities.

In the context of a Maripark, smart data management enables seamless integration of environmental monitoring, aquaculture operations, renewable energy performance, and asset-protection systems, supporting adaptive management, regulatory compliance, and multi-user cooperation (including civilian and defense actors) while maintaining strict data security and access-control protocols. These real-time and near-real-time data streams provide the essential input to the Data Hub and Digital Twin.

Smart monitoring systems are designed to capture both short-term variability and long-term trends, including climate-sensitive parameters such as temperature anomalies, stratification, and extreme events.

2.2. Data Hub: the core of integration, interoperability, and governance

The Maripark Data Hub (DH) is a centralised knowledge platform that governs, integrates, and distributes environmental and operational data throughout the EMP lifecycle. It supports data ingestion, standardisation, traceability, access control, reporting, and interoperability with external systems.

The Maripark Data Hub serves as the single point of truth where heterogeneous data streams from the smart monitoring layer converge and are transformed into validated, interoperable datasets ready for advanced modelling (DTO) and regulatory reporting.

This centralised approach is mandatory to address the data complexity, the technologies implicated (DTO) and governance challenges inherent in a MU environment involving multiple private operators and public authorities.

The Spatial Data Infrastructure (SDI) is the geospatial component of the Data Hub. It provides harmonised spatial layers, mapping services, and visualisation tools that support marine spatial planning, compliance checks, cumulative impact assessment, and stakeholder communication.

The design of the Maripark DH and its SDI is aligned with international best practices for marine spatial planning data systems. It follows the methodological principles outlined in the MSPglobal Data Toolbox [12], which provides a stepwise framework for developing interoperable, scalable, and governance-ready SDIs for MSP and related environmental processes.

These principles include the early definition of data governance rules, clear separation between data production and data use, interoperability across administrative scales, and long-term maintainability. Embedding these principles within the Maripark EMP ensures compatibility with national MSP systems, European data portals, and future cross-border MU initiatives.

The security architecture of the Maripark Data Hub is also consistent with international best practices for marine data governance, as outlined in the MSPglobal Data Toolbox (IOC-UNESCO, 2024), which emphasises controlled access, data sovereignty, role-based governance, and the separation between data production and data use in multi-actor MSP contexts.

Main data driven functions:

Function	Requirement
Multi-source data ingestion	The Hub must be designed to ingest high-volume, continuous data feeds from the smart monitoring systems (environmental and operational), as well as periodic data from public authorities (EBS) and external models.
Standardisation	This is the crucial step of harmonisation. All data must be mapped to a Maripark data framework to ensure semantic consistency (terminology, units) and compliance with standards such as INSPIRE, ISO 19115..., mandatory for European data exchange. This guarantees interoperability across operators and with EU reporting systems (cf section III. - standardisation step).
Quality assurance and fusion (QA/QC Level 2)	Automated validation routines (second-level QA/QC) are run centrally to identify complex errors (e.g., cross-sensor drift). Data fusion integrates environmental (e.g., noise, turbidity) and operational (e.g., turbine logs, vessel traffic) parameters into unified spatio-temporal datasets required for cumulative assessment.
Security and access control	The Hub must implement encryption, role-based and attribute-based access control, and cybersecurity control. In some cases, dual-use constraints (civil + Defence) require fine-grained access control, data-segmentation mechanisms, and reinforced sovereignty principles to protect sensitive operational and surveillance data (cf section III).
Long-term archival and traceability	The Hub is responsible for the secure, long-term archival of all raw and processed data, ensuring traceability required for regulatory reporting cycles (MSFD, MSP Directive, EIA obligations) and scientific reproducibility.

Table 4: Data Hub data driven functions

The design of the Maripark Data Hub aligns with existing European marine data infrastructures, including HiSea [13], used in ULTFARMS, and the Sea2Land Navigator [14]. These two systems are highly complementary in terms of scope and functionality.

HiSea provides high-resolution, near-real-time environmental information services, with a strong focus on supporting the operational needs of offshore aquaculture and LTA, particularly within multi-use environments. It demonstrates how continuous data acquisition, quality control, and tailored analytics can support day-to-day decision-making for offshore production systems.

In parallel, the Sea2Land Navigator offers a multi-governance framework designed to harmonise data flows, reporting obligations, stakeholder roles, and cross-sector coordination in coastal–marine domains. Its governance templates and structured workflows directly support the creation of a transparent, interoperable, and shared monitoring framework for multi-use sites.

Combining the operational data-service capabilities of HiSea with the governance and interoperability architecture of the Sea2Land Navigator provides a powerful blueprint for the Maripark data hub. Such an integrated system would enable:

- Continuous, autonomous, and multi-source data acquisition,
- Structured data governance and harmonised reporting across operators,
- Seamless integration of environmental, operational, and regulatory datasets,
- Multi-user dashboards and decision-support tools,
- Alignment with EU initiatives such as the DTO [15].

This hybrid approach forms the foundation of what a Phase 1 and mostly Phase 2 Maripark platform should become: a central, powerful, multi-sector operational and environmental intelligence system enabling real-time monitoring, cumulative-impact assessment, EBA and adaptive management in complex multi-use offshore environments.

The DH is structured to accommodate both observed data and future-oriented datasets, including climate projections, ensuring traceability, scenario labelling, and long-term comparability. The integration of future-oriented environmental data, including climate projections, is addressed in detail in D4.3 [1]. In this report, these datasets are operationalised through the DH and the DTO across the EMP lifecycle. When climate projections are already available, as referenced scenarios mentioned in D4.3 [1], from authoritative sources, the DH provides a sufficient infrastructure to store, reference, and compare observed monitoring data against future climate trajectories. In this configuration, the EMP can assess trends, detect deviations, and ensure regulatory consistency. This approach is consistent with the climate-smart principles for MSP outlined in the MSPglobal International Guide [15].

2.3. DTO: the analytical engine for Mariparks future-oriented ecosystem-based approach

While smart monitoring (II.1) provides the sensory inputs and the Data Hub (II.2) acts as the central memory and governance layer, the DTO serves as the analytical brain of the Maripark.

A Digital Twin is defined as a dynamic virtual replica of a marine system combining observations, simulations, and predictions to support planning, forecasting, and adaptive management [16] [17]. In the specific context of Mariparks, the DTO moves beyond simple 3D visualization to become a tool capable of integrating intersectoral models and assessing the complex, cascading cumulative effects inherent to the MU environment and allow an EBA as recognized in OSPAR guidelines [8].

From experimental to operational monitoring

DTO are transitioning from experimental modelling tools to operational assets across the maritime and environmental sectors. Current applications demonstrate their capacity to integrate real-time observations, numerical modelling, and predictive analytics, paving the way for their application in complex MU settings.

Industrial and port applications: In the offshore energy sector, DTO are established for structural health monitoring. They optimize maintenance schedules for offshore wind farms by detecting structural anomalies through physics-based models and real-time data assimilation [18]. Similarly, in the port sector, DTO combine IoT sensor networks with hydrodynamic models to monitor sediment transport, manage dredging operations, and assess navigational risks in real-time (Porto de Leixões DT; [18]). These examples highlight the maturity of DTOs for operational and safety monitoring.

EBA: Beyond infrastructure, the use of DTO for environmental governance is expanding. In river basins and urban water systems, "Environmental Digital Twins" are applied to track pollution and support Integrated Water Resources Management [20]. In the marine domain, literature increasingly advocates for DTO as enabling tools for Ecosystem-Based Management (EBM). By simulating ecosystem responses to cumulative pressures, they allow managers to visualize "invisible" stressors (e.g., underwater noise, chemical dispersion) and test mitigation strategies before implementation.

While existing DTO excel in mono-use optimization (wind energy) or specific environmental assessments (water quality), a gap remains in integrating both dimensions. On a longterm vision, the Maripark DTO aims to bridge this gap by fusing operational industrial data with ecological monitoring to address the unique challenges of MU interactions, aligned with MSPD objectives.

Figure 7: Mariparks operational monitoring design [7]

2.3.a Core functions for Mariparks EMP

Function	Explanation
Real-time state estimation	Through data assimilation, the DTO integrates multi-source inputs, sensor networks, gliders, remote sensing, turbine logs, to maintain an up-to-date representation of the environmental conditions within and around the Maripark. The DTO maintains an up-to-date representation of environmental conditions, filling the spatial and temporal gaps between sampling points.
Cumulative effect assessment – EBA	Unlike traditional monitoring which isolates stressors, the DTO models the interaction of multiple pressures (noise, nutrient inputs, vessel traffic, habitat modification). This is essential for regulatory support, including MSFD descriptors and Natura 2000 sensitivity assessments.

Scenarios-based simulation	The DTO facilitates risk-informed decision-making. Stakeholders can simulate the consequences of operational changes, such as the impact of dredging on aquaculture cages or turbine load changes on underwater noise before they occur. The DTO provides an analytical sandbox for testing short-term and seasonal variations in: • nutrient dynamics and water quality, • sediment transport and deposition, • underwater noise propagation, • habitat connectivity and species distribution, • interactions among co-located uses (wind–aquaculture–OPV). These simulations are essential for designing monitoring strategies based on expected system vulnerabilities. A "monitoring-by-design" approach now advocated in the literature [20].
Early warning system	By comparing real-time data against predicted thresholds, the DTO acts as a predictive alarm system, alerting operators to risks such as gear drift, HABs, or structural anomalies.
Adaptive management	Generating alerts, guiding monitoring adjustments, and validating mitigation efficiency.

Table 5: Digital Twin core functions for Mariparks EMP

The Digital Twin is not a prerequisite for incorporating climate projections into the EMP. Its added value lies in exploring system responses and multi-use interactions under future conditions, rather than in storing or referencing climate data.

2.3.b Challenges and limitations

The implementation of the DTO must remain realistic regarding current constraints:

- Uncertainty: biodiversity and benthic models remain subject to high uncertainty compared to physical models [21].
- Data availability: restricted offshore access and harsh weather limit sensor maintenance and data continuity.
- Governance: operators may be reluctant to share sensitive operational data.
- Technical readiness: especially for high-frequency assimilation and multi sector integration at scale (cf. EDITO perspectives in Section IV).

These challenges confirm the need for strong governance and robust standardisation in the Data Hub (Section II.2) before data enters the Digital Twin, as well as the progressive deployment strategy presented in Section III.

The Data Hub is the central knowledge platform of the EMP. It integrates a SDI for mapping and visualisation and may interface with a Digital Twin when modelling and scenario simulation are possible or required. Advanced analytical tools, including artificial intelligence and machine learning, may support data processing, anomaly detection and scenario analysis, but are not considered prerequisites for EMP implementation.

The three-pillar architecture is summarised in the following figure:

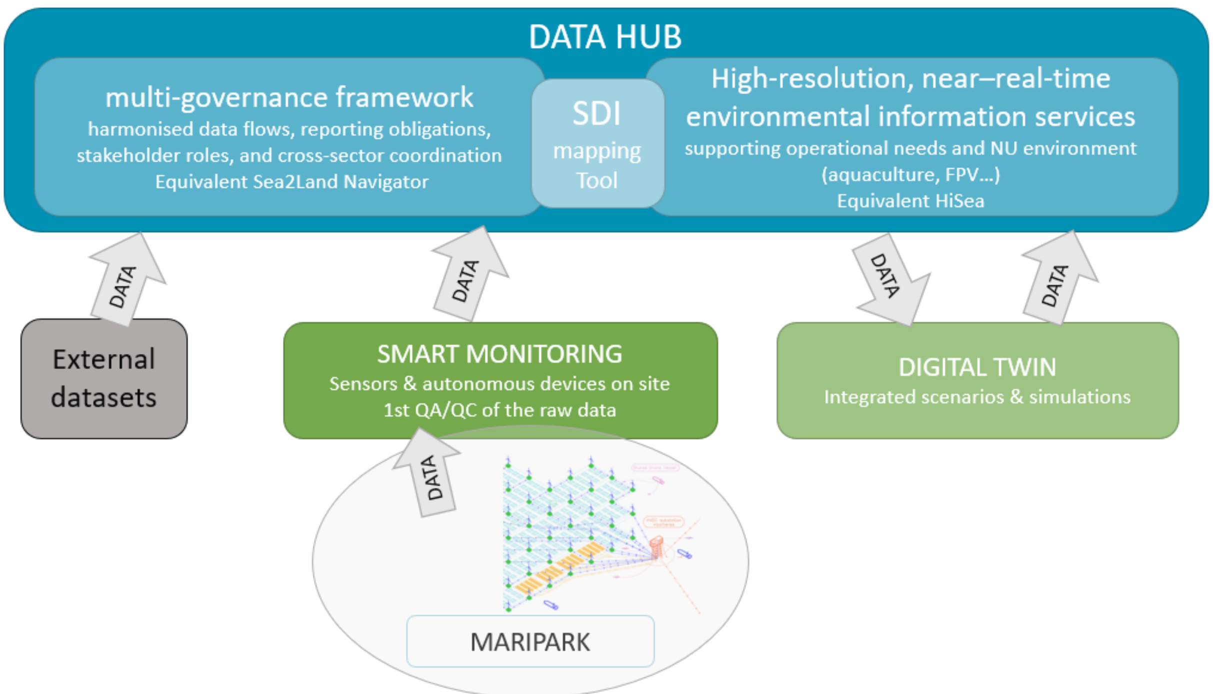

Figure 8: Data flows through Mariparks EMP technological components

III. Conceptual EMP Framework for Mariparks

This introduction frames the EMP not as a static reporting exercise but as a dynamic governance tool rooted in EBM, supported by digital technologies, and designed for multi-use marine spaces. The subsequent sections elaborate on each step of the framework, from scoping and initialisation to reporting and adaptive management, highlighting operational procedures, data flows, and recommended methodologies.

The stepwise structure of Section III directly reflects lessons learned from recent MU pilots (ULTFARMS and UNITED), notably regarding offshore robustness constraints, governance clarity, and progressive system integration.

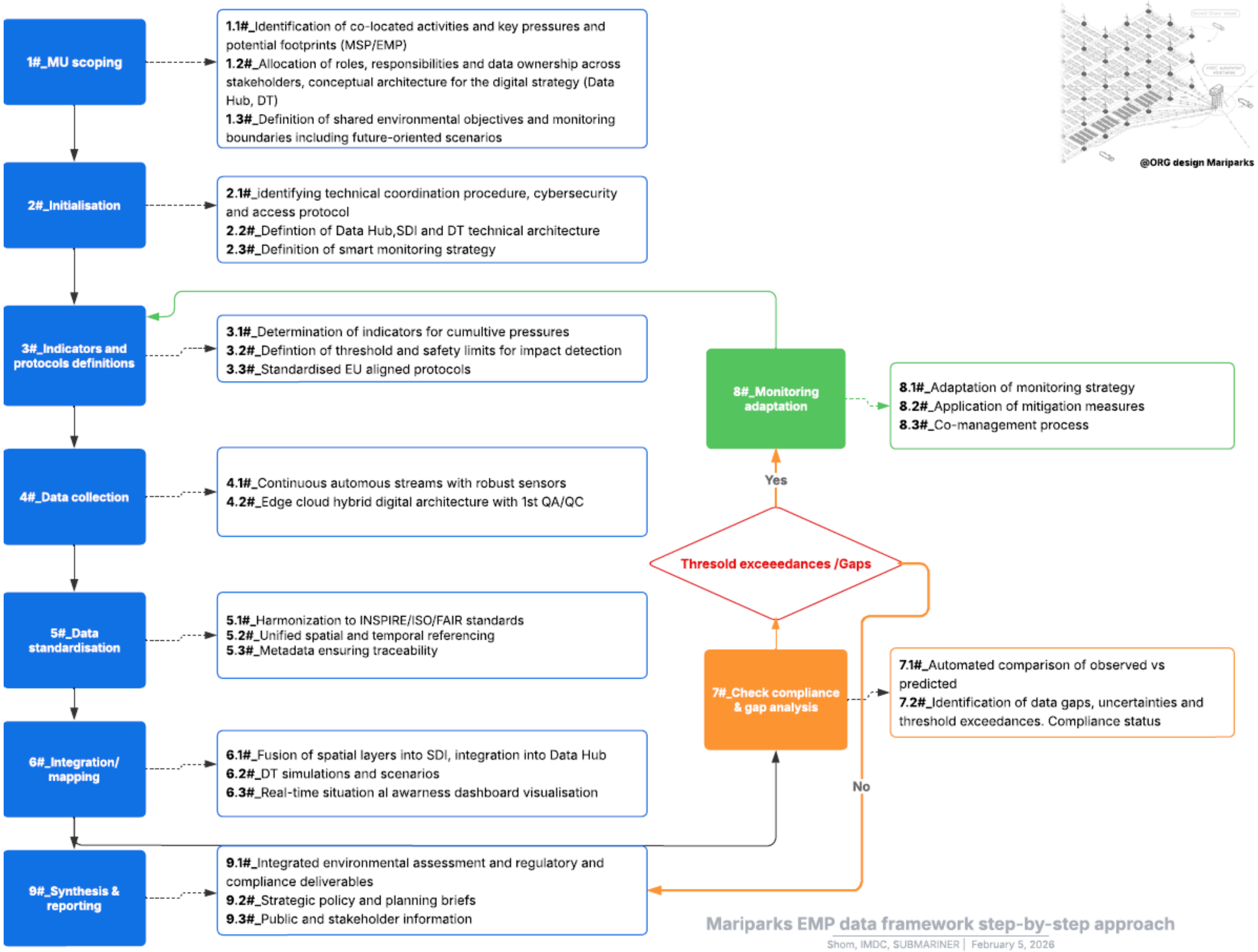

Figure 9: Mariparks EMP data framework step-by-step approach

3.1. #MU scoping

The identification of co-located activities and their potential spatial and environmental footprints provides a first understanding of the functional mix and associated pressures in the MU (further details are found in D.4.3 [1]). The MU scoping step constitutes the conceptual foundation of the EMP, it applies an EBA to examine interactions, cumulative pressures, and potential trade-offs. Rather than confirming predefined configurations, MU scoping supports an iterative process in which environmental considerations can inform, refine, or challenge initial scenario assumptions.

A defining innovation in this framework is that scoping already incorporates the first steps toward a Maripark DH and DTO. Instead of developping the digital twin only during monitoring or operational phases, the scoping process establishes the conceptual model of the system — the spatial boundaries, environmental compartments, baseline parameters, and sector interactions - that will later be integrated into the digital twin environment. Studies such as Schmitt et al. [22] and the EU's Destination Earth (DestinE) [23] initiative demonstrate that early definition of system structure significantly improves the quality and operational usefulness of marine digital twins.

Stakeholder engagement is also embedded into MU scoping, reflecting a long-standing finding in literature that collaborative governance enhances both effectiveness and legitimacy of marine spatial planning [24] [25]. Rather than treating stakeholders as later-stage consultees, their knowledge and concerns shape the identification of key receptors and pressures from the start. For example, small-scale fishers may identify locations of sensitive spawning grounds or gear conflict hotspots that are not visible in formal datasets, while environmental NGOs may highlight pressures on vulnerable species. This collective input helps refine the initial structure of the data hub and digital twin and ensures that the EMP focuses on areas where risks, uncertainties, and socio-ecological dependencies are most significant.

MU scoping explicitly integrates long-term climate projections (2030–2050–2070) to frame site selection, ecosystem sensitivity, and multi-use feasibility under future environmental conditions, in line with the future-oriented data framework defined in D4.3 [1].

Inputs	✓ MSP constraints, MSFD objectives, EBS/EIA results ✓ Environmental baseline and ecosystem functioning knowledge ✓ Stakeholder knowledge, use patterns, and institutional mandates.
Outputs	✓ Conceptual ecosystem & MU interaction model (pressures, receptors, flows) ✓ Priority environmental and operational risks ✓ High-level allocation of strategic roles among stakeholders (monitoring contributor, data owner, decision authority, responder) (cf NESBp T4.1 & T4.2) ✓ Conceptual architecture of the Maripark Data Hub and Digital Twin ✓ Identification of climate-sensitive receptors and potential climate refugia / risk zones ✓ Temporal horizon aligned with climate scenarios (2030–2050–2070).
Enabling components	✓ DH, DTO

Table 6: MU scoping operational summary

3.2. #Initialisation

The initialisation phase translates the conceptual understanding developed during scoping into the technical and organisational infrastructure required for an operational, data-driven EMP. Within the Maripark framework, this phase is particularly crucial because it establishes the architecture of the DH and the DTO, the data governance arrangements, and the multidisciplinary workflows that will support long-term monitoring and adaptive management.

A core principle of the initialisation phase is that data governance precedes data collection. This aligns with best practices in marine observation networks (e.g., EMODnet, Copernicus Marine Service; [26]), where early establishment of metadata conventions, data interoperability rules, and quality-control protocols greatly improves long-term usability. The environmental data managed within a Maripark involve different standards, resolutions, and ownership structures, ranging from public environmental monitoring datasets to proprietary data from offshore developers. Detailed standardisation procedures are addressed in Section III.5.

The initialisation phase establishes the centralised DH that will serve as the backbone for EMP analysis and reporting. This hub ensures interoperability with national MSP systems and allows public authorities, operators, and researchers to access relevant data at appropriate levels. Drawing inspiration from integrated information systems such as the Norwegian BarentsWatch and France's Shom data architectures. In line with the MSPglobal Data Toolbox [12] recommendations, the initialisation phase prioritises the definition of the SDI architecture and data governance framework before large-scale data acquisition. This sequencing is critical to avoid fragmentation, loss of metadata, and incompatibility between monitoring datasets generated by different MU actors.

Cybersecurity and data protection are embedded within this governance-by-design approach, ensuring secure data flows, controlled access, and trust among public and private stakeholders. It guarantees a robust balance between institutional transparency and the protection of sensitive industrial, commercial, and environmental datasets through tiered access protocols.

The digital twin framework is progressively established during initialisation. This involves formalising the structure defined during scoping into a computational model: identifying the state variables (e.g., temperature, nutrient levels, species abundance), the processes linking them (e.g., larval drift, habitat connectivity), and the human-driven pressures (e.g., noise emissions, fishing effort, aquaculture nutrient release).

Both the DH and the DTO are configured jointly during initialisation, ensuring that data governance rules, interoperability standards, and access rights are consistently applied across monitoring, modelling, and reporting functions. Finally, the smart monitoring strategy is technically specified. This involves defining the communication architecture (IoT gateways, acoustic telemetry…) and the platforms to be deployed (smart moorings, autonomous docks…). The specific selection of sensors and their sampling frequencies will be aligned with the indicators and protocols defined in Section III.3.

During initialisation, the selection of reference climate scenarios (e.g. SSP2-4.5 and SSP5-8.5) [27] and time horizons is formalised, ensuring consistency across indicators, modelling, and compliance assessments throughout the EMP lifecycle.

Inputs	✓ Conceptual ecosystem & MU model from scoping (III.1) ✓ EBS and EIA datasets and metadata ✓ MSP constraints and regulatory requirements ✓ Identified stakeholders and strategic roles.

Outputs	✓ Operational data governance framework (roles, access levels, data flows, cybersecurity policy) ✓ Selection and specification of the SDI for the Maripark Data Hub ✓ Functional architecture of the Maripark Data Hub ✓ Initial Digital Twin model structure (state variables, processes, pressures) ✓ Defined workflows for data ingestion, QA/QC, and model updating ✓ Defined smart monitoring technical strategy ✓ Reference climate scenarios and temporal horizons adopted for the Maripark.
Enabling components	✓ Smart Monitoring, DH, and DTO

Table 7: Initialisation operational summary

3.3. #Indicators and protocols definition

The definition of indicators and monitoring protocols represents the methodological backbone of the EMP. It is at this stage that baseline knowledge from scoping, EBS and EIA is translated into operational tools to evaluate the environmental status and guide adaptive management. As established in Part II, the monitoring framework follows an EBA to capture interactions between co-located activities.

The detailed indicator examples presented in this section focus on floating photovoltaic systems and aquaculture. This choice reflects the outcomes of Task 4.4, which identified these building blocks as among the most frequently explored and technically plausible multi-use configurations within current Maripark scenario designs. Their use here does not imply prioritisation or guaranteed feasibility but serves to illustrate how the EMP framework can be applied to multi-use combinations that are considered particularly relevant at this stage of development. Indicators constitute the primary entry point for the design of the monitoring system. Consequently, the number, type and spatial distribution of sensors are not predefined, but derive from the selected indicators, targeted pressures and site-specific conditions. This ensures a modular and scalable monitoring approach, avoiding unnecessary over-instrumentation while maintaining relevance and cost-effectiveness.

In practice, indicator definition can be divided into two complementary steps. The first step integrates results from EBS and EIA studies to identify the most relevant **pressures, receptors, and ecosystem services** at risk. For example, in a Maripark that combines offshore wind and aquaculture, key pressures may include underwater noise, sediment resuspension, nutrient enrichment, and physical disturbance of benthic habitats. Relevant indicators could then include benthic community composition, fish abundance and diversity, water column nutrient concentrations, and presence of sensitive species such as marine mammals or migratory seabirds [28][29].

In addition, experience from offshore aquaculture pilots such as from ULTFRAMS project shows that **food safety and sanitation indicators**, such as biotoxin levels, harmful algal blooms and microbiological contamination, are essential complements to ecological indicators, as they link environmental conditions to production safety and regulatory compliance. Including these indicators in EMPs helps anticipate operational risks and ensures that environmental change is assessed not only in ecological terms but also in relation to human health and socio-economic viability (more information in the Annex 1). This phase also identifies **threshold values** or reference conditions, which serve as benchmarks for detecting deviations and potential impacts.

The following table shows environmental monitoring indicators for Low-Trophic Aquaculture in OWF:

Impact	Reason for Monitoring	Indicator(s)	Methods
Water Quality	Detect eutrophication, hypoxia, or changes in local chemistry due to aquaculture	Nutrient concentrations (N, P, Si)	*In-situ* sensors, CTD (Conductivity, Temperature, Depth) sensors, optical DO sensors, water sampling & lab analysis
		Dissolved oxygen (DO)	
		Turbidity levels	
Phytoplankton & Primary Productivity	Assess food availability for filter feeders and risk of harmful algal blooms	Chlorophyll-a concentration	Remote sensing, fluorometers, microscopic analysis
		Phytoplankton species composition	
Benthic sediment conditions	Evaluate organic enrichment and anoxia, and benthic habitat changes	Sediment grain size	Sediment grabs/cores, benthic surveys
		Organic carbon content	
		Redox potential	
Biodiversity & Ecosystem Interactions	Track changes in local species richness, attraction of fish, and potential displacement	Species abundance	Underwater video surveys, eDNA sampling, trawl/ROV surveys
		Diversity indices	
		Presence of invasive species	

Carbon & Nutrient Cycling	Assess ecosystem services such as carbon sequestration and nutrient removal	Carbon burial,	Sediment cores, Total Organic Carbon (TOC) content
		Nutrient uptake by seaweed	
Hydrodynamics (currents, mixing)	Understand how aquaculture structures interact with wind farm foundations and influence water flow	Current velocity	ADCP (Acoustic Doppler Current Profiler), hydrodynamic modelling
		Turbulence intensity	
		Drag coefficient (Cd)	
Interactions with Wind Farm Infrastructure	Monitor biofouling, structural integrity, and potential conflicts	Biofouling biomass	Diver/ROV inspections, structural sensors, biofouling scraping
		Corrosion rates	
		Structural load changes	
Birds	Aquaculture farms may attract seabirds (roosting/foraging) increasing collision risk with turbine blades, or conversely, deter them due to activity	Collision rates	Visual survey, radar & camera systems
		Bird flight height & trajectory	
Marine Mammals	Operational noise from turbines combined with increased vessel traffic for aquaculture maintenance may disturb marine mammals	Ambient noise levels	Noise mapping, visual surveys
		Presence/Absence counts	

Table 8: LTA main indicators

The following table shows environmental monitoring indicators for OPV in OWF:

Impact	Reason for Monitoring	Indicator(s)	Methods
Light attenuation / Shading	Reduced light under OPV affects algae, benthic communities	Photosynthetically Active Radiation (PAR)	satellites, PAR sensors, radiometers
		Kd (light extinction)	
Surface temperature	OPV can warm or cool surface water, affecting stratification	Sea surface temperature (SST) anomalies	CTD sensors, satellites
		Current velocity	CTD, ADCP

Hydrodynamics (currents, mixing, stratification)	Reduced wind fetch and shading can alter mixing regimes	Stratification depth	
Water quality	Altered mixing & shading affects nutrient & oxygen availability	Nutrient concentrations	In-situ sensors, optical DO sensors, water sampling & lab analysis
		Dissolved oxygen	
Primary productivity	OPV influences phytoplankton growth	Chlorophyll-a concentration	Satellites, fluorometers
Benthic sediment conditions	Shading and deposition may change benthic habitats	Organic carbon content	Sediment cores, benthic cameras
		Redox potential	
		Benthic suspended sediments, composition	
Interactions with OPV Infrastructure	OPV structures create habitat → fouling, invasive species	Species composition, biomass	ROV, settlement plates

Table 9: OPV main indicators

The second step focuses on the organisation of indicators according to spatial and functional clusters, such as those proposed in the Marine Spatial Planning data Framework (MSPdF) [30]. Clustering indicators facilitates data management, improves comparability, and aligns monitoring with management objectives. Typical clusters include biodiversity and habitats, hydrodynamics and sediment dynamics, water quality, socio-economic uses, and infrastructure interactions. Within each cluster, specific protocols are defined for data collection, frequency, analytical methods, and reporting. For instance, standardized protocols for benthic monitoring may involve sediment grabs and imagery surveys, while water quality may rely on continuous sensor data combined with periodic laboratory analyses [31], [32].

Linkages between indicators are explicitly considered at this stage to ensure that monitoring captures interactions between pressures and ecosystem components. Integrated models and, where available, DTO simulations support the identification of priority indicators and critical combinations of variables relevant for cumulative impact assessment, as well as testing for future activities or climate change projections [33] [34]. For example, simulations of current variability and sediment transport around wind farm foundations and aquaculture installations can inform the selection and spatial allocation of benthic and water-quality indicators. This targeted use of modelling outputs helps optimise monitoring design and supports adaptive adjustments of protocols over time.

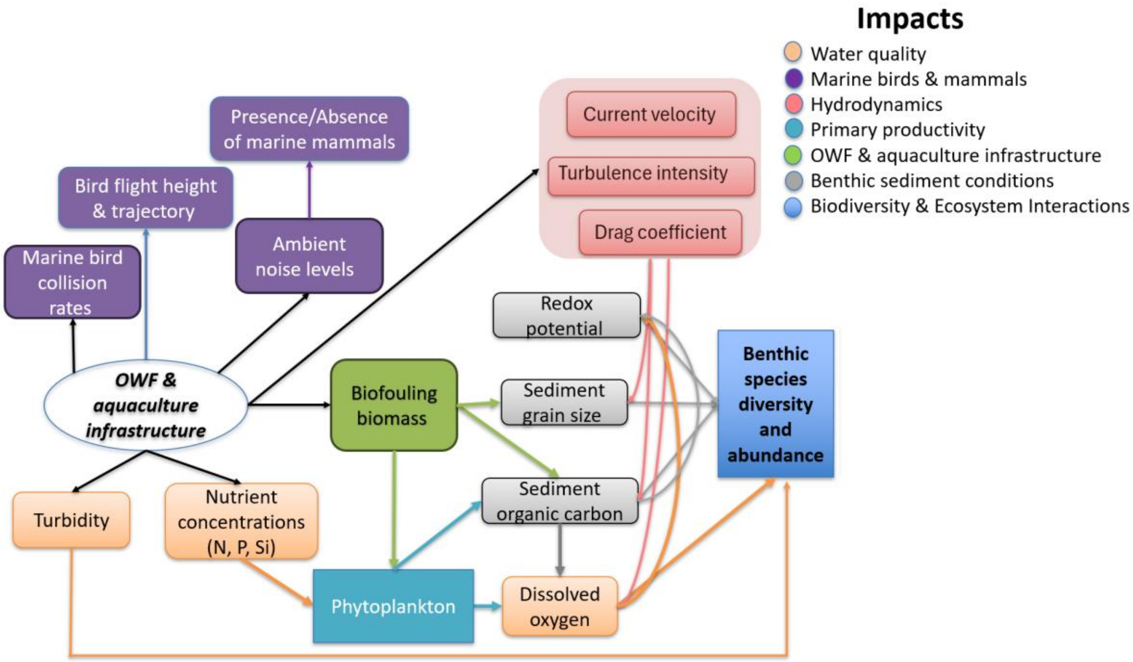

Figure 10: Linkages between environmental monitoring indicators for LTA in OWF

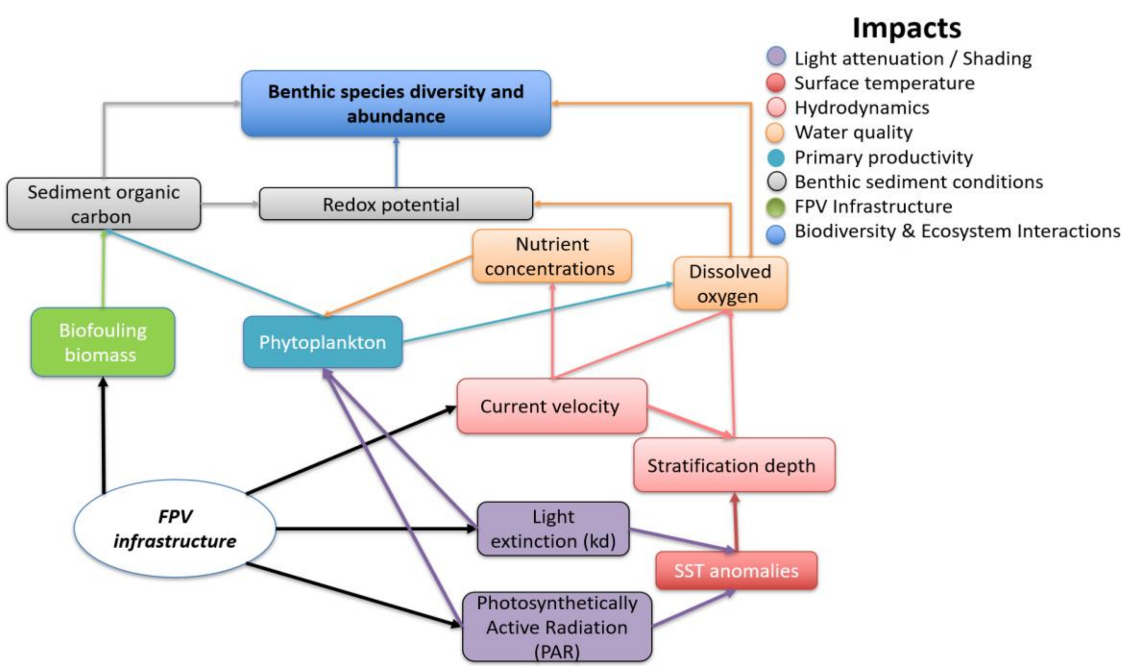

Figure 11: Linkages between environmental monitoring indicators for offshore OPV in OWF

By structuring indicator selection and monitoring protocols within an ecosystem-based perspective, and by allowing the targeted use of integrated models and DTO outputs where available, this phase ensures that the EMP can capture key interactions within the Maripark ecosystem. It provides a robust and scalable framework to support cumulative impact assessment and adaptive management across multiple sectors, while remaining compatible with different levels of data and technological maturity.

Inputs	✓ MU scoping results, EBS and EIA findings ✓ MSP and MSFD objectives and constraints ✓ Stakeholder knowledge on uses, sensitivities, and conflicts ✓ Existing scientific references and regulatory thresholds.
Outputs	✓ Set of priority environmental and operational indicators aligned with MU cumulative pressures (EBA) ✓ Reference conditions and thresholds for impact detection ✓ Standardised monitoring protocols (methods, frequency, coverage).
Enabling components	✓ Smart Monitoring, DH in advanced configurations.

Table 10: Protocols and indicators definition operational summary

3.4. #Data collection

The data collection phase represents the operationalisation of the indicators and protocols defined previously. It transforms methodological intentions into observations, measurements, and datasets that describe the evolving environmental state of the Maripark. Data collection involves a blend of **in-situ monitoring**, **remote sensing**, **model-derived data**, and **operational activity reports** from users of the Maripark (cf. details in Annex 2).

All incoming streams are integrated directly into the DH to be standardized and then in the DTO.

A critical component of this phase is the First-level QA/QC (as detailed in Section II.1), where raw data from smart sensors are automatically validated, filtered at the point of acquisition to ensure the reliability of an integrated system.

Observed monitoring data are complemented by downscaled regional climate projections, enabling comparison between current conditions and future expected ranges.

Inputs	✓ Validated indicators, thresholds, and protocols (III.3) ✓ Monitoring design (methods, frequency, spatial coverage) ✓ Operational activities and MU configurations ✓ Regulatory monitoring requirements (MSFD, Natura 2000, food safety).
Outputs	✓ Time-stamped observations describing the evolving state of the Maripark ecosystem ✓ validated and filtered data ready to be integrated in the DH.
Enabling components	✓ Smart Monitoring, DH in advanced configurations.

Table 11: Data collection operational summary

3.5. #Data standardisation

Data standardisation is a central pillar of a coherent and transferable EMP. The standardisation strategy will be defined at the initialisation phase (III.2) and apply systematically at this stage. Every data point generated by the Smart Monitoring system is automatically tagged with metadata following the MSPglobal 'Metadata Profile' [12]. This ensures that even the most technical datasets (acoustics, vibration) are discoverable and usable within the broader SDI for cross-disciplinary studies. It is essential that monitoring protocols align with international and European standards, such as ISO 14031 for environmental performance indicators, INSPIRE for spatial data interoperability, and guidance from EMODnet and Copernicus MarineService.

As detailed in D4.3 [1], all datasets follow a rigorous step-by-step approach to transform raw data into actionable information:

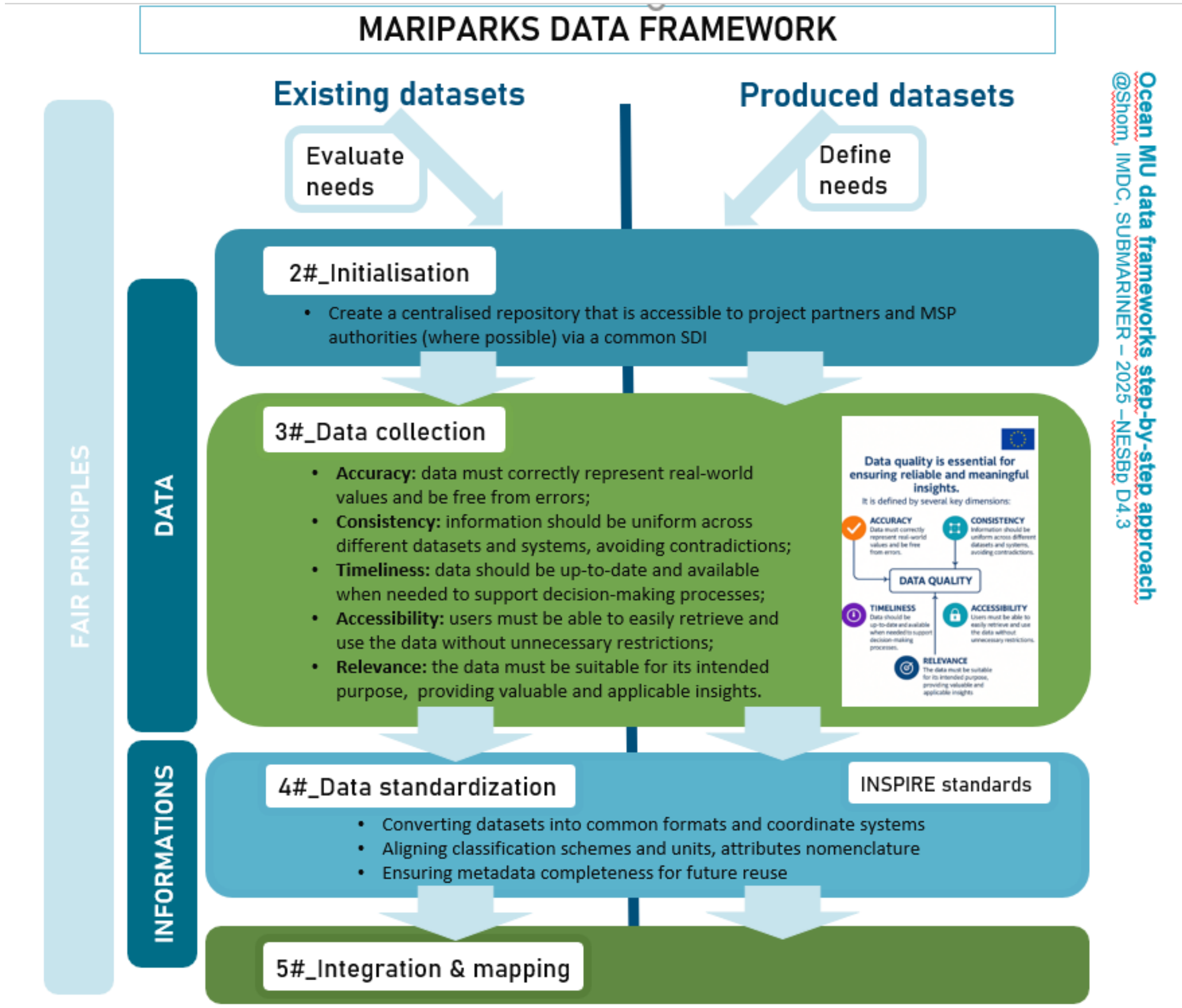

Figure 12: Mariparks data framework and hamonisation step [1]

For the DH and the DTO these standardised inputs ensure that model simulations and scenario analyses maintain a consistent baseline and remain comparable over time. Automated quality checks, addressing Accuracy, Consistency, Timeliness, Accessibility, and Relevance, help detect inconsistencies early, reducing the analytical burden in later EMP phases.

Although often perceived as an administrative step, standardisation plays a strategic role in supporting the EBA by ensuring that all ecosystem components and monitoring methods speak the same “language”.

Inputs	✓ First-level QA/QC validated datasets from smart monitoring systems ✓ Public datasets (EBS, national monitoring, Copernicus, EMODnet) ✓ Operational data from Maripark users (OWF, aquaculture, vessels) ✓ Predefined metadata templates and governance rules (from III.2).
Outputs	✓ Harmonised and secured datasets compliant with INSPIRE, ISO, FAIR standards ✓ Common spatial and temporal reference frameworks ✓ Metadata catalogues ensuring long-term traceability and reuse.
Enabling components	✓ Smart Monitoring, DH, DTO.

Table 12: Data standardisation operational summary

3.6. #Integration and mapping

This integration operates at two complementary levels. First, validated datasets are spatially integrated within the SDI of the Data Hub, enabling mapping, compliance checks, and cross-sectoral spatial analyses. Second, a deeper integration occurs within the DTO where these spatial datasets are transformed into dynamic model inputs supporting simulation, forecasting, and cumulative impact assessment. Geospatial visualization enables:

- Identification of environmental patterns,
- Detection of hotspots and anomalies,
- Integration with MSP layers and multi-use compatibility,
- Cumulative impact assessment.
- Compliance checks and adaptive management.

Mapping outputs feed directly into compliance checks and adaptive management by providing intuitive dashboards for both authorities and operators. This stage ensures full interoperability with national MSP and EIA/SEA processes, allowing the Maripark to be managed as an integral part of the wider marine territory.

The SDI enables spatial visualisation of future climate exposure, supporting climate-informed zoning, compatibility checks, and MSP alignment. The Digital Twin integrates climate projections into dynamic simulations, assessing long-term ecosystem responses and infrastructure resilience under multiple climate pathways.

Inputs	✓ Standardised and quality-controlled datasets (from III.5 Data standardisation) ✓ MSP layers (zoning, restrictions, cables, Natura 2000, shipping lanes) ✓ Environmental sensitivity maps and baseline spatial datasets ✓ Operational footprints of MU activities (OWF, aquaculture, OPV, vessels).
Outputs	✓ Integrated spatial layers hosted in the Maripark SDI (Data Hub) for environmental patterns, hotspots, and anomalies ✓ Cumulative pressure and impact maps supporting EBA assessments ✓ Visual dashboards feeding compliance checks and adaptive management ✓ Digital Twin simulations and scenarios.
Enabling components	✓ Data Hub (SDI), DTO.

Table 13: Integration and mapping operational summary

3.7. #Compliance checks & gap analysis

Compliance checking is a systematic comparison between observed environmental conditions and the regulatory, technical, or ecological thresholds defined in earlier EMP steps. This includes evaluating conformity with environmental legislation (e.g., MSFD descriptors, Water Framework Directive standards), license conditions from EIAs, and operational mitigation obligations. The Digital Twin, in advanced configurations, plays a crucial role here by offering simulated baseline scenarios and predictive envelopes that help distinguish natural variability from human-induced change.

Gap analysis complements compliance verification by identifying where monitoring is incomplete, insufficiently precise, or poorly aligned with pressures introduced by evolving multi-use activities. Gaps may arise from limited spatial coverage of sensors, inadequate temporal resolution, methodological inconsistencies between operators, or emerging ecological phenomena, such as novel species interactions or unanticipated underwater noise propagation patterns.

Inputs	✓ Standardised and validated monitoring datasets (environmental & operational) ✓ Regulatory thresholds and objectives (MSFD descriptors, WFD standards, Natura 2000 targets) ✓ EIA commitments, licence conditions, and mitigation measures ✓ Baseline reference states and model envelopes from the DTO ✓ Spatial layers from SDI (uses, pressures, habitats, infrastructure)
Outputs	✓ Compliance status assessment against regulatory, ecological, and operational thresholds supporting EBA ✓ Identification of monitoring gaps, including: – spatial and temporal coverage gaps – insufficient resolution or precision – emerging pressures linked to MU interactions – Climate risks
Enabling components	✓ Data Hub (SDI), DTO in advanced configurations

Table 14: Compliance checks & gap analysis operational summary

3.8. #Monitoring adaptation

Monitoring adaptation is the phase where the EMP becomes dynamic, ensuring that environmental management evolves in response to new evidence, unexpected interactions, or operational changes in the Maripark. In line with adaptive management principles and the ecosystem-based approach, this stage enables continuous refinement of indicators, sampling frequency, technologies, and mitigation measures.

One key function of this phase is identifying conflicts between uses or disturbances that may compromise ecosystem functions or operational safety. Examples include interactions between fishing gear and subsea cables, behavioural displacement of marine mammals due to construction noise, or sediment mobilization affecting aquaculture installations. When threshold exceedances or emerging conflicts are detected, adaptive mitigation measures may involve temporary exclusion zones, gear modifications, seasonal adjustments to activities, rerouting of vessel traffic, or deployment of additional monitoring technologies (e.g., passive acoustic devices, turbidity sensors).

The involvement of stakeholders is essential. Incorporating co-management principles ensures that fishers, developers, authorities, and scientists jointly interpret monitoring results and co-design responses. This enhances legitimacy, compliance, and local ecological knowledge integration. In a multi-use environment, shared understanding of data and risks reduces tension and facilitates early intervention measures. Operational procedures and responsibilities, including the potential role of dedicated governance bodies, are addressed within T4.1.

Monitoring adaptation relies primarily on the Data Hub to ensure traceability, transparency, and continuity of decisions across EMP cycles. When available, the Digital Twin further strengthens this phase by enabling scenario-based testing of alternative management options. This predictive capacity helps adjust monitoring plans proactively rather than reactively.

Monitoring adaptation concludes with updated protocols, revised spatial prioritisation, enhanced sensor networks, or new modelling routines, ensuring that the EMP remains relevant, responsive, and aligned with the evolving ecological and operational reality of the Maripark. Automated monitoring systems may be complemented, where relevant, by periodic in situ verification to ensure data reliability and support decision-making.

Climate projections inform proactive adaptation of monitoring design, allowing early adjustment to emerging risks such as marine heatwaves or species range shifts.

Inputs	✓ Standardised and validated monitoring datasets (environmental & operational) ✓ Regulatory thresholds and objectives (MSFD descriptors, WFD standards, Natura 2000 targets) ✓ EIA commitments, licence conditions, and mitigation measures ✓ Baseline reference states and model envelopes from the DTO ✓ Spatial layers from SDI (uses, pressures, habitats, infrastructure).
Outputs	✓ Adapted monitoring strategy to ensure continued relevance and regulatory alignment, including: – revised indicators and thresholds – adjusted sampling frequency and spatial coverage – deployment or removal of monitoring technologies ✓ Adaptive mitigation measures, such as: – temporal or spatial restrictions – gear or operational modifications – conflict-avoidance measures between MU activities ✓ EBA adjustments, explicitly addressing: – cumulative effects – cross-sector interactions

	– ecosystem functions and resilience ✓ Inputs to stakeholder coordination and co-management processes.
Enabling components	✓ Smart Monitoring, DH, DTO in advanced configurations.

Table 15: Monitoring adaptation operational summary

3.9. #Synthesis and reporting

Synthesis and reporting constitute the culmination of the EMP, translating the diverse data streams collected across the Maripark into coherent, decision-supporting outputs for managers, stakeholders, and regulatory authorities. In a multi-use marine environment, this step is essential not only for regulatory compliance but also for ensuring transparency, co-management, and adaptive environmental stewardship. The reporting process consolidates results from biological, physical, and socio-economic indicators, integrating them into a holistic assessment of the environmental status and the performance of mitigation measures.

A key element of this phase is the **integration of monitoring results into structured narratives that reflect ecosystem functioning**. Rather than reporting indicators in isolation (e.g., benthic indices, nutrient concentrations, or noise levels), synthesis aims to demonstrate how pressures interact and how ecosystem components respond collectively. This approach aligns with the principles of EBM, which emphasize the interconnectedness of species, habitats, ecological processes, and human activities [34]. For example, a seasonal increase in suspended sediment may be contextualized alongside changes in benthic community structure, aquaculture production cycles, and maintenance operations of offshore infrastructure.

Inputs	✓ Results of adaptive management decisions and performance of mitigation measures (Section III.8) ✓ Integrated datasets from Data Hub and SDI ✓ Digital Twin outputs and scenarios narratives (when available) ✓ Comparison with long term climate trends (referenced scenarios) ✓ Regulatory reporting requirements (MSFD, WFD, Natura 2000, Food Safety…) ✓ Metadata and data provenance records ensuring traceability and transparency.

Outputs	✓ Integrated environmental assessment – ecosystem status and cumulative multi-use pressures – cross-sector interactions and regulatory performance ✓ Regulatory and compliance deliverables – official EMP reporting packages for competent authorities – validated datasets formatted for European platforms – audit trails of data access and usage – certified metadata ensuring data sovereignty and integrity ✓ Strategic policy & planning briefs: – contributions to national MSP revisions – long-term climate resilience and adaptation roadmaps (aligned with IPCC) – transferable lessons learned for future Maripark replications ✓ Public and stakeholder information: – summaries for co-management bodies and local communities – interactive web-dashboards (via Data Hub, SDI) for real-time transparency.
Enabling components	✓ Data Hub.

Table 16: Synthesis & reporting operational summary

Following the definition of the EMP framework at the Maripark scale (Section III), Section IV presents an exploratory assessment of the potential role of the European Digital Twin of the Ocean (EDITO), announced in the Ocean Pact[1], in supporting Maripark EMP.

[1] https://oceans-and-fisheries.ec.europa.eu/european-ocean-pact_en

IV. Articulation between Mariparks and EDITO: data flows and complementary roles

Section IV examines how Mariparks EMP data could interface with EDITO as a supporting European infrastructure. While EDITO does not replace Maripark-level DTO components, it can contribute to data standardisation, interoperability and access to long-term environmental and climate projections, and provides relevant inputs for future upscaling and replication activities addressed under Task 4.5. In this context, EDITO can act as a bridge between private operational data and public marine spatial planning, supporting transparency, long-term climate resilience and the objectives of an integrated European Blue Economy.

4.1. Scope, components and maturity of EDITO

EDITO is conceived as a distributed and interoperable digital infrastructure that integrates marine data, modelling services and cloud-based computing resources to support analysis, simulation and decision-making in the marine domain[2]. Its scope encompasses three tightly linked components:

1. marine data, including in situ observations, remote sensing products and model outputs;
2. analytical services, including physics-based and AI-based models, workflows and scenario tools; and
3. cloud computing resources, enabling users to run analyses directly in the cloud without the need for local installations.

This infrastructure is designed to support the development of application-specific digital twins, for example for habitat suitability modelling, cumulative impact assessment, climate adaptation, or optimisation of marine uses such as offshore energy and aquaculture.

At present, EDITO has reached a level of maturity that allows researchers and technically skilled users to work efficiently with its data lake and processing services, benefiting from direct access to Copernicus Marine Environment Monitoring Service (CMEMS), EMODnet and selected project-based datasets. While core applications are technically functional, they are not yet fully seamless for end users, and available

[2] https://edito-infra.eu/european-digital-twin-ocean-introducing-edito-infra/

computing resources remain constrained, although extensible through connections to High-Performance Computing (HPC) infrastructures.

By 2028–2030, EDITO is expected to evolve into a fully operational European marine digital infrastructure, offering robust, scalable and user-oriented services supporting policy implementation, marine planning and market-oriented applications from local to European scale. This evolution aligns closely with the long-term needs identified for EMP and Ocean MU systems such as Mariparks.

4.2. Types of marine applications supported

EDITO is not optimised for a single application domain but rather provides a generic, modular infrastructure designed to support a wide range of marine applications. These include ecosystem and food-web modelling, Cumulative Impact Assessment (CIA), MSP support, climate projections and scenario analysis, OWE planning, aquaculture optimisation, environmental monitoring, and environmental risk assessment. This breadth makes EDITO particularly relevant for multi-use contexts, where environmental, operational and socio-ecological dimensions must be analysed jointly.

4.3. Compatibility between EDITO and the Maripark EMP framework

The Maripark concept — combining WOF, OPV systems, aquaculture, nature restoration and, where relevant, Defence or surveillance functions — is in principle compatible with EDITO's architecture. However, the practical effort required for integration depends on the cloud-readiness, interoperability and data governance maturity of individual Maripark components. Integration may range from relatively rapid deployment (for cloud-native models and standardised data streams) to more substantial development efforts where legacy systems or non-standard data formats are involved.

EDITO's data lake already hosts copies of CMEMS and EMODnet datasets and allows the ingestion of additional regional, local and project-specific datasets. Importantly, the platform supports the integration of user-provided monitoring data, including near-real-time data streams, which is particularly relevant for EMP implementation. There are no inherent spatial or temporal resolution constraints imposed by EDITO; in practice, the main limiting factor for site-scale or high-resolution simulations is the computing budget available through connected HPC providers.

EDITO is well suited to hosting Maripark-specific local digital twins, integrating interactions between energy production, aquaculture activities, biodiversity, maritime traffic and climate drivers. This aligns directly with EDITO's next development phase and with the EMP logic described in this deliverable, where Digital Twin components support cumulative impact assessment, early warning systems and adaptive management.

4.4. Data management, governance and security considerations

EDITO follows emerging conventions for data formats, metadata and quality control, aligned with existing CMEMS and EMODnet practices. While these conventions are not yet fully regulated, they provide a clear pathway for harmonisation and interoperability with European marine data infrastructures.

The platform supports multi-actor data contributions, allowing researchers, operators, authorities and private-sector actors to contribute data through personal or project-based accounts. In this sense, EDITO could act as a hub for Maripark-related datasets and analytical tools, and potentially as a marketplace matching data supply and analytical demand.

At present, most EDITO components are open and public. The handling of sensitive or restricted-access datasets (e.g. commercially sensitive operational data or surveillance-related information) is still under discussion. Mechanisms to manage confidentiality, access control and data security will need to be developed in close collaboration with the EDITO development team. Importantly, the platform's evolution is demand-driven, and projects such as Mariparks can play a role in shaping future governance features by clearly articulating operational needs.

4.5. Support to MSP, SEA and basin-level upscaling

EDITO has strong potential to support basin-level coordination platforms such as the Greater North Sea Basin Initiative (GNSBI) and similar regional cooperation mechanisms. The EDITO development team envisages the platform as a possible host for shared datasets, indicators and analytical tools supporting cross-border coordination.

In the context of Strategic Environmental Assessment (SEA), EDITO can provide both access to relevant environmental data and a suite of analytical tools for scenario exploration and impact assessment. Existing and emerging applications — including habitat suitability modelling, pollution tracking, and "what-if" scenario simulators — illustrate how EDITO can support cumulative and strategic assessments beyond project-level EIAs.

Overall, EDITO is well positioned to support adaptive management cycles central to the EMP framework by serving as a central platform for data storage, visualisation and scenario analysis, without requiring local software installations.

4.6. Mariparks EMP into EDITO for basin-level data interoperability

The integration of a Maripark EMP into EDITO should follow a progressive, use-driven approach, aligned with both the current maturity of the platform and the phased development of Mariparks.

Key recommendations for EDITO integration:

- **Prioritise data richness and continuity**
  High-frequency, long-term environmental measurements across space and time are among the most valuable contributions a Maripark can make to EDITO. Even where spatial comparability between Mariparks is limited, consistent temporal datasets significantly enhance cumulative assessment and model calibration.
- **Adopt cloud-ready, interoperable data products**
  Monitoring data and models should be structured to comply with EMODnet and Copernicus conventions wherever possible, facilitating rapid ingestion into EDITO and reuse beyond the project.
- **Use EDITO as a complementary layer, not a replacement**
  EDITO should complement, not replace, existing Data Hub and Digital Twin components developed at Maripark level. The EMP must remain functional at site level, while EDITO provides added value for scaling, cross-site comparison and regional assessment.
- **Plan early for data governance and access control**
  Projects should engage early with the EDITO development team to clarify data access, confidentiality and governance needs, particularly when combining environmental monitoring with operational or surveillance-related datasets.
- **Exploit EDITO for upscaling and policy interfaces**

EDITO is particularly well suited for translating EMP outputs into MSP, SEA and basin-level coordination processes. Indicators, thresholds and scenario outputs developed for Mariparks should be designed with this broader policy interface in mind.

- **Engage actively with EDITO's evolution**

  The platform is still evolving. Clearly articulated project needs — especially from complex MU systems like Mariparks — can directly influence future EDITO functionalities, including support for restricted-access data, automated alerts and adaptive management workflows.

V. Recommendations

The development of EMP for Mariparks requires a progressive and realistic approach. Given that fully integrated Mariparks do not yet exist, the priority is not to deploy the most advanced technologies immediately, but to structure a framework capable of evolving as technical, governance and data capacities mature.

The prioritisation of actions should therefore follow three guiding principles:

- Robustness before sophistication: favour reliable and maintainable systems rather than complex ones that fail or are hard to maintain or operate offshore;
- Progressive integration: move stepwise from mono-use monitoring to multi-use interoperability and finally to digital-twin supported adaptive management;
- Governance and data clarity first: no digital solution can compensate for unclear roles, fragmented responsibilities or incompatible datasets

This framework is not conceived as a fixed blueprint but as a scalable architecture that can support different maturity levels of Mariparks, from current single-use sites to future fully integrated multi-use systems.

Key messages from D4.6

- Start from what already exists

EMP development should build on current MSP, MSFD and EIA practices rather than replace them. Mariparks do not require inventing a completely new regulatory universe but linking existing instruments through integration and interoperability.

- Invest first in governance, not only in technology

Experience from multi-use pilots shows that incidents are rarely caused by a lack of data, but rather by unclear responsibilities, fragmented mandates and insufficient data-sharing agreements. Governance design is therefore a technical requirement, not an accessory. In particular, the governance of the data value chain and ownership needs to be clear from the beginning and be studied in T4.1.

- Digital Twins are enablers, not prerequisites

Digital Twins should be deployed progressively and in line with data availability, sectoral cooperation and operational needs. The EMP must be functional without a full Digital Twin, while clearly identifying the added value such tools will bring when mature. Data quality may hamper the value of a Digital Twin: "garbage in, garbage out".

❖ **MU requires integrated indicators**

Conventional EMPs evaluate environmental and operational dimensions separately. Mariparks need integrated indicators capturing interactions between co-located activities, cumulative pressures and ecosystem responses, and linking them to management triggers.

❖ **Climate resilience must be embedded from the start**

Mariparks will operate for over several decades. EMP design must therefore integrate future environmental baselines, climate projections and long-term ecosystem change to avoid locking in maladapted infrastructure and management strategies.

❖ **Use EDITO for regionalisation and upscaling of EMPs**

By providing a shared digital infrastructure for data access, modelling and scenario analysis, EDITO offers a pathway to translate site-specific EMP results into regional and basin-level insights. Its value lies in supporting cumulative impact assessment, MSP and strategic environmental planning, rather than replacing local EMP implementation.

This upscaling role requires cybersecurity-by-design and robust data-governance mechanisms to ensure secure data exchange, controlled access and trust across multi-actor and cross-border MSP contexts.

❖ **In the context of MSPD revision, EMP and EBA should be mentionned**

The MSD Directive is under revision as part of the European Ocean Act, this should introduce climate-smart maritime spatial planning and integrate the need of harmonization with other Directives. It will also support a 'multi-use by design' approach to tackle spatial squeeze in certain areas. Therefore, it is recommended to mention and detail the EMP and EBA approach as they are fit for the needs which will be introduced by the revision.

Conclusion

The conceptual framework presented in this report proposes an EMP specifically adapted to the emerging concept of Mariparks. It recognises that Mariparks are still largely theoretical constructs, with few real-world examples beyond pilot-scale multi-use projects, and that both technological and governance components are evolving.

The proposed EMP should therefore be understood as:

- Conceptual but operationally oriented,
- Adaptive rather than prescriptive,
- Capable of accompanying Mariparks from their earliest mono-use configurations to more integrated and exploratory MU systems.

It bridges three levels:

- (i) Environmental baseline and assessment,
- (ii) Operational monitoring and data governance,
- (iii) Future-oriented integration of smart monitoring, data hubs and Digital Twins.

The progressive path toward integrated Mariparks, from phase 0 to phase 2 as defined in T4.4, is summarised below.

Phase	Description	Characteristics of EMP	Enabling components
Phase 0 – Current situation (mono-use)	Single-use offshore sites operating independently (e.g. OWF, aquaculture).	Sectoral, regulatory monitoring (EIA). Limited data sharing.	- Basic monitoring infrastructure, - Operator-specific data management systems (silos).
Phase 1 – Pilot MU	Experimental co-location of activities within a shared marine space (UNITED/ULTFARMS pilots).	Partial interoperability. Joint monitoring of MU-specific indicators & cumulative pressures, initiation of scenario.	- Basic smart monitoring integration (eDNA, drones), - Data Hub prototype, first cross-sectoral data protocols. - Conceptual DTO

Phase 2 – Integrated Maripark	Coordinated multi-use site with shared governance and digital support.	Real-time data integration, early-warning systems, and climate-resilience monitoring.	- Robust and integrated smart monitoring, - Automated data flows for near real-time acquisition - Secure interoperable Data Hub, - Operational DTO components.

Table 17: EMP adaptation by Phase

While Task 4.4 and the Maripark Evaluator address the economic and political feasibility of different multi-use configurations, the EMP framework developed in D4.6 provides the scientific and environmental reference needed to assess their ecological implications. The two tools are complementary but serve distinct purposes. The EMP establishes a robust, science-based framework to evaluate whether a given Maripark configuration, under specific environmental and governance conditions, meets regulatory requirements and contributes to the ambition of net positive ecological impact defined in the Mariparks concept. Issues related to governance, including data stewardship and institutional arrangements, are addressed in Task 4.1, to which the EMP contributes by clarifying the central role of data availability, quality and accessibility for effective environmental assessment and long-term monitoring.

By grounding environmental assessment in high-level scientific standards, transparent indicators and structured data management, the EMP acts as a safeguard, ensuring that environmental limits, cumulative impacts and ecosystem responses are systematically and transparently considered alongside economic and political decision-making. Given the long operational lifetime of Mariparks, the relevance of both economic scenarios and environmental assessments depends on their ability to account for long-term environmental variability. The EMP therefore highlights the importance of climate-informed scenarios as boundary conditions for the definition and evaluation of Maripark configurations, ensuring that monitoring strategies and indicators remain meaningful over decadal time scales.

Transferability is a core design principle of the proposed framework. Its phased approach, combined with clearly identified enabling components, ensures that it can be replicated in different Member States and sea basins, adapted to national permitting systems, and progressively aligned with basin-level coordination mechanisms and EU initiatives such as EDITO and EMODnet.

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Annex

Annex 1: MU pilots lessons learned from ULTFARMS and UNITED projects

Offshore low-trophic aquaculture (LTA) in multi-use (MU) settings is emerging rapidly in the North Sea and Baltic Sea. Experience from ULTFARMS shows that environmental monitoring in these offshore and MU environments must extend beyond compliance and risk detection. Effective monitoring becomes a strategic enabler for quantifying ecosystem services, ensuring safety, maintaining operational performance, and supporting upscaling of LTA within offshore wind farms. The findings from ULTFARMS provide important insights for designing Environmental Monitoring Plans (EMPs) for Mariparks.

Monitoring Must Demonstrate Ecosystem Benefits, Not Only Detect Impacts

Traditional monitoring focuses on mitigating negative impacts such as benthic disturbance, eutrophication or species displacement. ULTFARMS demonstrates that LTA systems—especially mussels and macroalgae—can provide positive ecosystem functions, notably nutrient and carbon removal. Measuring nitrogen and carbon content in harvested biomass offers a reliable proxy for quantifying removal at farm scale, which is particularly important offshore where dilution and physical transport complicate direct water-column measurements.

Experience from the UNITED project further reinforces this shift from impact-only monitoring towards benefit-oriented assessment. UNITED demonstrates that multi-use platforms can reduce cumulative environmental impact risks relative to single-use configurations, but that such benefits remain invisible unless explicitly captured through monitoring frameworks designed around pressure–pathway–receptor relationships (UNITED D4.2). In particular, UNITED highlights the need to monitor not only pressures and state variables, but also ecosystem service pathways such as habitat provision, nutrient cycling, carbon sequestration, and fisheries exclusion effects (UNITED D4.4). Without such indicators, Environmental Monitoring Plans risk underrepresenting the net environmental performance of Mariparks and multi-use systems.

Implication for EMPs:

EMPs should explicitly integrate **biomass-based nutrient and carbon accounting** as a standard element, contributing evidence for licensing, nature-inclusive design, compensation schemes, and spatial planning.

Offshore Conditions Require Robust, Automated and Weather-Independent Monitoring

Harsh offshore conditions—strong currents, high waves, storms and long periods without safe access—create major constraints for both operations and monitoring. ULTFARMS confirms that activities such as maintenance, sampling or inspections can be impossible for weeks or months, making consistent human-based monitoring unfeasible. Monitoring systems therefore need to operate autonomously, transmit data remotely, and withstand prolonged exposure to extreme conditions.

UNITED pilot experience confirms that offshore monitoring feasibility is governed as much by health and safety, access windows, and operational logistics as by scientific ambition. Monitoring approaches relying on diver-based inspections or frequent vessel campaigns were repeatedly constrained by weather, distance offshore, and safety protocols. As a result, UNITED pilots increasingly relied on remotely operated vehicles (ROVs), fixed sensors, automated data acquisition, and integration of monitoring with routine operational inspections (UNITED D7.4).

Implication for EMPs:

Monitoring programmes must prioritise durable sensors, automated systems, remote transmission and early-warning mechanisms, supported by contingency protocols for infrastructure damage or extreme-weather events.

Multi-Use Settings Create Additional Monitoring Needs

Co-locating aquaculture within offshore wind farms introduces specific operational interactions and risks. Although restricted-access zones around turbines may reduce certain navigational risks, MU systems also generate new challenges:

- Potential for gear to detach, drift or interfere with turbine foundations or maintenance vessels.
- Increased mechanical loads and altered hydrodynamics.
- Increased consequences of equipment failure due to proximity to energy infrastructure.

ULTFARMS pilots observed that structural integrity monitoring becomes even more critical in MU contexts, requiring more frequent and automated surveillance.

UNITED further demonstrates that multi-use monitoring challenges extend beyond physical interactions to include coordination between multiple operators, overlapping responsibilities, and shared infrastructure (UNITED D7.4). Monitoring responsibilities for environmental parameters, structural integrity, and safety-related observations were often distributed across actors, requiring clear protocols and interfaces. UNITED pilots show that effective monitoring in MU settings depends on explicitly defining roles, data ownership, and escalation pathways, and on integrating environmental indicators with operational monitoring of infrastructure condition, loads, and access constraints, in line with the pressure–pathway–receptor logic of the UNITED Assessment Framework (UNITED D4.2).

Food Safety Monitoring Remains Essential and Highly Regulated

Offshore LTA must comply with strict EU food-safety regulations. ULTFARMS Deliverable 6.1 confirms that **food safety and sanitation indicators** are a critical complementary component of Environmental Monitoring Plans for offshore low-trophic aquaculture, as demonstrated by experience from ULTFARMS and other European pilot projects. Beyond their relevance for consumer protection and market access, food safety indicators provide an essential interface between environmental conditions and production viability, reflecting how ecosystem dynamics directly affect aquaculture operations. In practice, pilots consistently highlighted the importance of monitoring **harmful algal blooms (HABs), biotoxins and microbiological contamination**, not only to comply with national and EU regulatory requirements, but also to anticipate operational risks linked to changing environmental baselines and cumulative pressures offshore. Integrating these indicators into EMPs strengthens the feedback loop between environmental status, ecosystem health and socio-economic sustainability, and supports adaptive management by linking ecological monitoring with legally binding food safety thresholds. Details on the product monitoring for offshore LTA suggested in ULTFARMS Deliverable 6.1 Review of the monitoring requirements and strategies for offshore low-trophic aquaculture are presented in the table below (Table 3, ULTFARMS Deliverable 6.1).

	Variable	Reason for monitoring	Indicator(s)	Legal obligation	Methods
Food quality	Nutritional values	Product quality	Proteins, lipids, carbohydrates	DK*, DE, NL	Samples, extractions, chemical analyses
Food quality	Size, flesh/shell ratio	Product quality	Size, flesh/shell ratio		Measure and weigh representative samples
Food quality	Wet and dry weight of algae	Product quality	Weight		Weigh representative samples
Food safety	Microalgae in water)	Products safe for consumption	Dinoflagellates, Diatoms	DK, DE*, NL, BE	FluoroProbe: chlorophyll in vivo measurement, fluorescence of algae (excitation spectra "fingerprints"); HPLC; mouse bioassay
Food safety	Heavy metals from water (in seaweed)	Products safe for consumption	Hg, Pb, Zn and Cu, Iodine	DE*, BE	Tissue samples, extractions, ICPMS (Inductively Coupled Plasma - Mass Spectrometry
Food safety	Algal toxins concentration in fresh mussel flesh	Products safe for consumption	ASP-, PSP-, DSP-, Yesso-toxins	DK, DE*, NL, BE	Lab analysis (HPLC)
Food safety	Indicator for bacterial contamination	Products safe for consumption	Cultivable bacteria	DK, DE, NL, BE	Cultivation of samples on agar plates in lab, counting of colonies
Food safety	Indicator for fecal contamination	Products safe for consumption	*E.coli*	DK, DE, NL, BE	Cultivation of samples on selective agar plates in lab, counting of colonies
Food safety	Preventing Salmonella outbreak	Products safe for consumption	Salmonella	DE, NL, BE	Cultivation of samples on selective agar plates in lab, counting of colonies, PCR when indicated
Food safety	Micro-algal cell count in Water	Products safe for consumption	Potential toxic microalgae	DE, NL, BE	Filtrating water samples and counting under microscope/binocular
Food safety	Contaminants in mussel flesh	Products safe for consumption	list of appr. 30 variable - PCBs, PKA, Heavy metals.... depending on country	DE, NL, BE	Lab analysis of mussel sample

Conditional legal obligations

Implication for EMPs:

Monitoring plans must clearly delineate food-safety compliance while allowing synergies with ecological monitoring—for example, using environmental sensors to help anticipate HAB-related risks.

Practical Constraints Require Feasible, Tiered Monitoring Approaches

One of the consistent findings from ULTFARMS is the mismatch between ideal monitoring objectives and real offshore feasibility. Vessel time represents the largest cost in offshore operations, while sensors suitable for long-term deployment offshore remain costly and technically demanding. As a result, legally required parameters tend to be monitored at minimum levels, while many non-mandatory ecosystem indicators remain unmonitored due to cost constraints.

Implication for EMPs:

EMPs should adopt a **tiered approach**, distinguishing between:

1. **Legally required parameters** (e.g., food safety, MSFD/WFD indicators)
2. **Core ecological indicators** essential for MU sustainability
3. **Optional modules** for positive-effect monitoring, research or innovation

Cost-efficiency should be addressed through **joint monitoring**, co-location of sensors on wind infrastructure, and cooperation with research institutions.

Detailed recommendations related to ULTFRAMS/UNITED projects Align EMPs with offshore constraints and risks.

Monitoring plans must account for limited site access, strong wave conditions and restricted maintenance windows, using risk-based approaches and early-warning indicators to protect infrastructure, workers and the environment.

- Prioritise remote, autonomous and robust monitoring technologies. Offshore constraints make high levels of automation essential. EMPs should rely on durable sensors, imaging systems and autonomous platforms capable of continuous operation in harsh conditions.

- Integrate operational, ecological and food-safety monitoring.

  MU sites combine industrial structures, biological production and ecosystem functions. EMPs must therefore jointly cover gear integrity, biodiversity indicators, water quality, and compliance with established EU food-safety requirements for seaweed and bivalves.

- Avoid monitoring gaps caused by unclear regulation.

  Because offshore LTA is emerging and regulatory frameworks remain incomplete, EMPs should apply the precautionary principle and rely on best available science rather than waiting for formal monitoring obligations.

- Promote shared, cost-efficient monitoring infrastructures.

  Monitoring offshore is expensive. Cost-sharing between wind operators, aquaculture producers, researchers and authorities—along with the use of EU data infrastructures (EMODnet, DTO)—is essential for long-term data continuity.

- Track both negative and positive environmental effects.

  EMPs should evaluate not only potential impacts but also restoration potential and ecological enhancement (habitat creation, biodiversity benefits, filtration effects), supporting the nature-inclusive design intent of MU systems.

- Design adaptive, flexible EMP.

  Monitoring strategies should evolve over time, allowing refinement of parameters, new technologies, and alignment with updated regulations or site-specific findings.

- Ensure strong baseline and post-deployment monitoring.

  At least one year of baseline data is needed to distinguish natural variability from project impacts. Post-deployment monitoring should track both immediate and long-term effects.

- Enable co-design between industry, science and authorities.

Successful EMPs depend on collaboration: industry ensures operational relevance, researchers ensure methodological rigour, and authorities ensure regulatory alignment and long-term integration.

Annex 2: Data collection, detailed process

In-situ monitoring remains the backbone of environmental observation and includes vessel-based surveys, diver or ROV inspections, benthic sampling, fishery-independent trawl surveys, and fixed instrumentation such as buoys and seabed landers. For example, benthic communities may be monitored through grab sampling and dropcamera footage, while mobile species such as fish or marine mammals require acoustic surveys, passive acoustic monitoring (PAM), or automated video observations [35]. Biological data are complemented by physical measurements: currents, waves, turbidity, temperature and chemical parameters including nutrients, dissolved oxygen, and contaminants. These data are essential for evaluating the state of habitats and ecosystem functioning and provide critical inputs to the digital twin initiated at the scoping phase.

A distinguishing element of the proposed framework is the explicit integration of data collection with the **Maripark digital twin**. As new data are collected, they continuously inform and calibrate the modelling system, improving predictions of ecosystem responses and operational conditions. Likewise, outputs from the digital twin can indicate where intensified or targeted monitoring is needed, such as areas of predicted sediment deposition, high collision risk for birds, nutrient hotspots, or zones of potential activity conflict. This feedback loop allows data collection to become smarter, more efficient, and increasingly aligned with management priorities [32] [33].

Equally important is the integration of **operator-reported datasets**. Activities inside the Maripark, such as turbine maintenance, aquaculture operations, fishing activity, vessel movements, or nature restoration actions, generate operational data that are critical for environmental interpretation. Examples include aquaculture stocking densities, feed input records, turbine operation logs, lighting and noise profiles, and AIS/VMS vessel tracking [36]. When integrated through the common data hub, these datasets provide valuable context for interpreting observed environmental variability and potential impacts.

Throughout the data collection phase, rigorous **quality assurance/quality control (QA/QC)** ensures that the incoming data meet the standards defined earlier. Metadata completeness, instrument calibration, temporal consistency, and error-checking protocols are applied systematically. Harmonisation with INSPIRE and EMODnet conventions enhances interoperability, supporting seamless integration with data from public authorities or neighbouring projects.

Ultimately, the data collected during this phase form the empirical foundation for compliance assessments, adaptive management, cumulative impact analysis, and stakeholder reporting. By combining traditional surveys, smart monitoring, remote sensing, operator reporting, and digital twin modelling, the framework supports a comprehensive and ecosystem-based understanding of the Maripark environment—one that reflects the real multiplicity of pressures and fosters evidence-based, shared decision-making.

Summary

This deliverable D4.6 presents a conceptual Environmental Monitoring Plan (EMP) framework supporting the development of Mariparks as multi-use offshore infrastructures. The framework applies an Ecosystem-Based Approach to identify cumulative pressures, ecosystem responses and trade-offs across co-located activities, supported by smart monitoring strategies, structured data hubs and digital twin applications as analytical tools. Given the multi-decadal lifetime of Mariparks, the EMP highlights the importance of climate-informed scenarios as boundary conditions for monitoring design. Its modular and phased structure supports transferability across Member States and sea basins, and alignment with EU initiatives such as EMODnet and EDITO.

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